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REVIEW

Impact of Global Warming on Water Cycle Changes in the Western Himalaya: A Review

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ABSTRACT

The Western Himalaya, often termed the "Water Tower of Asia," is experiencing critical hydrological changes due to global warming. This review synthesizes current scientific knowledge on climate-driven alterations in the region's water cycle, assessing impacts on ecosystems, agriculture, energy security, and local livelihoods. We conducted a systematic literature review of peer-reviewed studies (2000–2024) from Scopus, Web of Science, and regional databases, supplemented by case studies and observational/modeling data. Key themes include cryospheric loss, shifting precipitation, river flow variability, and hydrological extremes. Key findings indicate that (1) temperature increases (0.2–0.5°C/decade) have accelerated glacier retreat (up to 20–30% mass loss in some basins) and reduced snow cover (5–15% decline since 2000); (2) altered precipitation patterns have increased rainfall dominance, elevating flood risks while reducing groundwater recharge in arid zones; and (3) river discharge shows declining dry-season flows but higher peak flows, threatening water security for over 200 million downstream inhabitants. These findings underscore the urgent need for integrated, cross-scale strategies combining scientific innovation, indigenous knowledge, and adaptive policies to enhance resilience. We highlight critical gaps in high-altitude monitoring and call for transboundary cooperation to mitigate escalating climate risks. This systematic review uniquely contrasts Western Himalayan hydrology with that of the Central and Eastern regions and benchmarks policy gaps, offering a roadmap for climate-resilient water governance.

Keywords: Western Himalaya; Water Cycle; Climate Change; Glacier Retreat; Hydrological Adaptation

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1. Introduction

The Western Himalayas are a key and very important part of the entire Himalaya Mountain range, and are vital to the hydrological and ecological stability of the whole of South Asia [1]. This portion, which is part of Jammu and Kashmir, Ladakh, Himachal Pradesh and Uttarakhand in India and in adjoining regions of Pakistan, Nepal and China, is the source of many of the large rivers such as the Indus, the Jhelum, the Chenab and the Sutlej. The rivers have created the lifeblood of the great agrarian and urban systems of the Indo-Gangetic as well as the Indo-Ganges plains, feeding hundreds of millions of people. The Western Himalaya is also considered the Water Tower of Asia as it plays a strategic role in guaranteeing the security of the waters in the region by supporting agriculture, hydropower, global ecology, and agricultural activities. Throughout the last several decades, the area under consideration has been under the significant climate change effect: the temperature increases, the precipitation becomes highly irregular, and the cryosphere deteriorates significantly. The changes are transforming the basic functioning of the hydrological cycle, including snow and melt, glacier mass balance, stream flows, soil moisture levels and evapotranspiration levels. The Himalaya has been identified by the Intergovernmental Panel on Climate Change (IPCC) and many regional assessments as a climate-sensitive, data-scarce region in which relatively small climatic changes may entail disproportionately large ecological and socio-economic impacts [2].

The high-altitude world has very high global warming conditions, and the warming can be swifter relative to world averages earlier than it was discovered that high-altitude regions enjoy elevation-dependent warming. Temperatures in the western Himalaya have shown a rise during the past 100 years, between 0.16 and 0.6 °C each decade and higher trends during winter and spring. The implications of this warming are far-reaching for the cryosphere of the region, which controls the timing and volume of runoff in the rivers of the Himalayas. Glacier melting, changes in snow to rain, and even snowmelt systems are all changing the hydrological patterns not only at the head of the mountains but also down the river to the people [3,4].

Glacier retreat is one of the most notable effects of climate change in the Western Himalaya. Several glaciological studies and remote sensing on glaciers through satellites have indicated that most of the small and medium-sized glaciers are melting very fast. These glaciers have shown a recession, and this impacts the availability of water, mainly in the summer, since water provided by the glaciers through melting usually keeps the river baseflows covered. At the same time, the provision of glacial lakes through the ice melt is the growth probability of glacial lake outburst floods (GLOFs), which are a major threat to the community and the infrastructure of the mountains [5].

Redistributions of precipitation patterns add to the hydrological perspective. The two prevailing weather systems, the Indian summer monsoon and western disturbances in winter, have an influence on the region. Changes in the timing, intensity and spatial distribution of these systems, caused at least partly by global warming, have given greater precipitation variability. The occurrence of extreme rainfalls has also become more common than before, coupled with increasing drought periods, a trend that has posed an increased threat of floods and droughts. Additionally, the evolving pattern of snowfall (this means fewer but heavier snow events) can apply to the snowpack stability, runoff timing, and recharging soil moisture availability [6].

Complex orography, variable microclimates, and scarce observations on meteorological conditions make the western Himalaya area more difficult to deal with in hydrological modelling and climate impact assessment. However, recent developments in remote sensing, automatic weather stations, and regional climate models are slowly enhancing the cognisance of the climate-stressed water cycle literature. Nevertheless, major research gaps continue to exist in the measurement of groundwater recharge and underground flows, as well as the interaction of cryospheric and hydrological systems [7].

The effects of the disruption of the water cycle are not only environmental but also socio-economic. **Figure 1** revealed the components of terrestrial water cycle [8]. Agriculture in communities of the mountain regions relies on regular snowmelt and spring runoff. Changes in water supply caused by climate change may cause crop failures, loss of food security, and drive people to relocate. In cities and lower plains, changes in river regimes also pose a threat to supplying water for domestic and irrigation and even hydropower. In addition, the Himalayan ecosystem, which supports a very wide flora and fauna, is also becoming susceptible to water deficiency, habitat loss, as well as changes in species territories due to climate change. It is on this background that this review seeks to synthesize existing scientific information on the effects that global warming is having on the water cycle in the western Himalaya. The literature revealed that the research in this field is increasing day by day, as displayed in **Figure 2**. The article will present a general account of what has been observed, how its modelling enhances case-specific experience, and what trends have been observed in great detail based on the following information:

- Trends in climate change in the region;
- the response on the cryospheric level;
- Alteration in precipitation and evapotranspiration;
- social, economic, and ecological repercussions;
- Data and modelling inadequacy;
- Adaptation and mitigation measures.

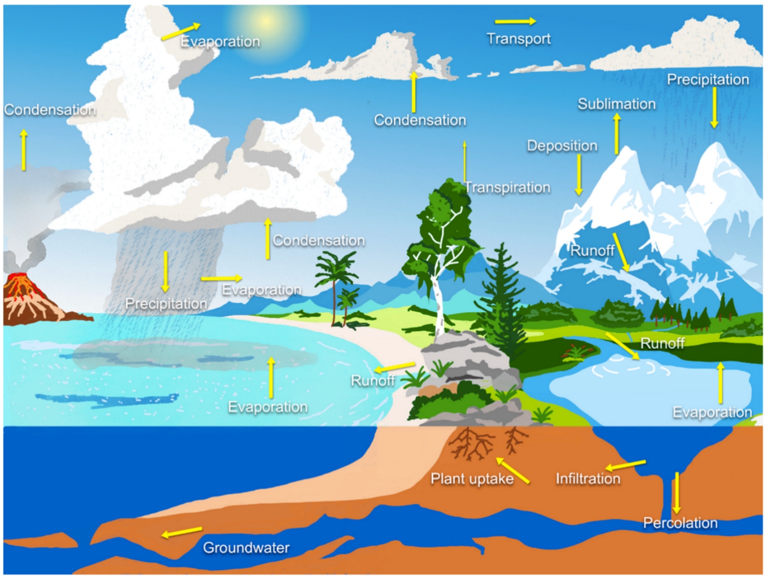

Figure 1. The Terrestrial Water Cycle and Its Components [8].

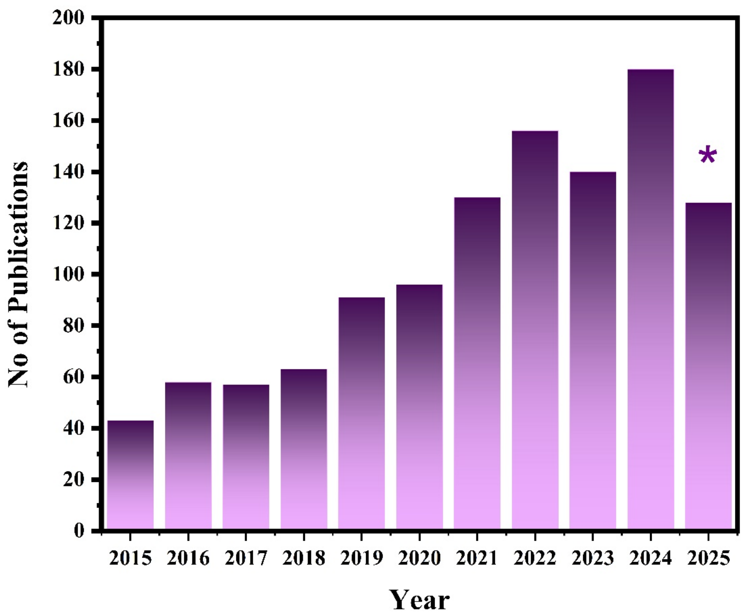

Figure 2. Number of Articles Published Per Year on the Review Title. The Information is Retrieved from Scopus with the Keyword "Impact of Global Warming on Water Cycle Changes in the Western Himalaya" on 16 July 2025.

The timing of this review is particularly relevant since policymakers, researchers, and the locals are becoming more interested in water management models that are less susceptible to climatic changes [9,10].

To formulate appropriate interventions, it is necessary to understand all the complicated effects of global warming on the hydrological cycle in this vulnerable mountain system. It requires a transcendental and cross-functional magnitude not only to respond to some of the existing weaknesses but also to develop the anticipated risks in the future scenario of climate change persistence. All in all, the western Himalaya represents the vanguard of climate change, where the modifications of the water cycle are not merely the signatories of global change but also the progenitors of local and regional disasters [11–13]. We believe that this review will shed light on these intricate relationships and help us make informed choices in the face of an uncertain hydrological future. Unlike prior reviews focused solely on physical changes, this work integrates cryospheric shifts, socio-ecological impacts, and policy responses, with explicit comparisons to Central/Eastern Himalayan systems. Although this manuscript does not propose a new analytical framework, it identifies critical gaps where future research could build comparative models, especially contrasting Western Himalaya with Central and Eastern segments in terms of policy responsiveness, hydro-climatic variability, and adaptation outcomes.

This review adhered to a systematic literature review framework, following PRISMA guidelines for transparency and reproducibility. We screened 320 peer-reviewed articles (2000–2024) from Scopus, Web of Science, and regional databases (e.g., ICIMOD, Himachal Pradesh University Repository) using keywords: Western Himalaya, water cycle, glacier retreat, hydrological adaptation. Inclusion criteria prioritized studies with:

Observational data (e.g., glacier mass balance, river discharge), Climate/hydrological models (e.g., CMIP6, SWAT), or Policy analyses (e.g., transboundary agreements, community adaptation).

2. Climate Change Trends in the Western Himalaya

The Western Himalaya has become a hotspot of climate change in the context of its topographic, atmospheric, and cryospheric setting. Being part of the greater region of the Hindu Kush Himalaya (HKH), the mountainous area shows high sensitivity to alterations in the global and regional climate patterns. Both observational and climate simulation data demonstrate with consistency that the western Himalaya is warming in a significant way, with changes in precipitation patterns and the emergence of extreme weather events as another feature. These weather patterns are directly related to changes in the area of the hydrological cycle [14].

2.1. Trends in Temperature and Height-Dependent Warming

The implications of the research conducted in the field of study cover strong results, which show that the temperatures in the Himalayas are increasing faster than the global average. The warming trends in the western Himalaya during the past few decades show an increment in mean annual temperatures by 0.16 °C to 0.6 °C per decade, conditioned on height, link arrangement and season. Warming is usually more rapid with increasing elevation, a process also described as elevation-dependent warming (EDW). This action is pushed by the mechanisms of feedback, like snow-albedo feedback (the less snow, the more the heat is absorbed) and cloud-radiation reflections.

Seasonal fluctuations in warming tendencies are also learned. Winters and springs have the more pronounced positive changes in temperatures as compared to summer and autumn, which greatly affect the level of snow accumulation and thawing processes [15]. For example, with warmer winters, there are changes in snowpack stability and timing of runoff due to less snow occurring and a greater prevalence of rain-on-snow events. A summary of observed temperatures is given in **Table 1**.

Table 1. Observed Climate Trends in the Western Himalaya (Past 50 Years).

Variable	Observed Change	Source/Notes
Mean annual temperature	+0.3°C to +0.6°C per decade	Stronger warming at higher elevations
Winter temperature	Increasing faster than summer	Affects snow accumulation and melt timing
Snowfall	A decrease in many areas	More rain-on-snow events observed
Precipitation pattern	More erratic, rise in extremes	Increased variability in monsoon & WD

2.2. Variability and Trends

In the western Himalaya, two main systems of precipitation can be considered as the determinants:

- Indian Summer Monsoon (ISM) that provides rainfall from June to September, and this rainfall is mainly concentrated on the southern slopes.
- Extratropical storms of the Mediterranean region, known as the Western Disturbances (WDs), cause winter precipitation (snowfall and rainfall) from November to March.

Recent reports depict that there has been no substantial and rounded pattern of overall annual precipitation over the whole of the western Himalaya; however, the distribution along with the intensity of precipitation has become shakier. There has been a fall in winter snowfall in some areas with warming, and extreme precipitation events, particularly the monsoon, have increased in others. Such spatial and temporal heterogeneity makes it hard to make predictions and plans.

Moreover, climate models show that there is an increase in rainfall and rainfall-to-snow ratios, especially in transitional seasons such as the months of March and November. The change is essential, as snowmelt will offer a temporary and even supply of water, whereas rainfall will create water runoffs that raise flood hazards [16].

2.3. Weather Disasters and Flash Flooding

More and more severe weather is on the rise over the western Himalaya: cloudbursts, flash floods, heat waves, and the like, as well as extreme spells of drought. The 2013 Kedarnath disaster in Uttarakhand and the 2021 Chamoli flash flood have brought concerns about the terrible possibilities of climate-induced hydrometeorological risks. The extremes tend to be associated with unusual warming, strong convective-type storms, and collisions between westerly disturbances and the monsoon system [17].

In the Himalaya, rainfall events of short duration and high intensities have also been on the increase, and this is likely to continue to encourage landslides and debris flows that are a real threat to life, infrastructure, and water resources along the narrow valleys in the Himalaya [18].

2.4. Climate Model Projections

Global and regional climate models (e.g., CMIP6, CORDEX South Asia) indicate persistent warming and an increase in high and low-priority precipitation in the next few decades. In deep-emission scenarios (e.g., RCP8.5 and SSP5-8.5), the western Himalaya may warm by the end of the 21st century by 3°C to 5°C, according to the altitude. It is also predicted that precipitation will be shorter and more intense on particular days, and will further enhance the chance of floods and dry weather.

Nevertheless, there are still uncertainties because of the rugged terrain and inadequate ground measurements. There has been an active endeavour to produce more accurate downscaled climate models and include high-resolution datasets to improve such projections [19].

2.5. Atmospheric and Cryospheric Feedbacks

Increasing temperature levels also trigger feedback effects that make climate change even stronger. For instance:

- Shrinking snow coverage leads to the decline of albedo, which enhances additional heating.
- Receding glaciers display dark-coloured surfaces of rocks, which capture a greater amount of sunlight.

Increased soil moisture and changes in vegetation cover may affect local humidity and energy balance, changing regional precipitation cycles.

These responses not only exacerbate warming but also increase the uncertainty of water availability in the periods of spring and summer when agriculture and hydropower are the most important.

To recapitulate, the western Himalaya is experiencing fast-changing climatic conditions, i.e., temperatures are rising, precipitation patterns are changing, and extreme events are on the rise. These are not purely academic trends, but they pose severe disturbances to the water cycle, environmental stability, and the lives of human populations in the region. This is because an appreciation and measurement of these changes is what comprises a proper evaluation of the larger hydrological effects, which are examined later in this review.

3. Cryospheric Changes and Impacts

The hydrological system of the western Himalaya relies on the cryosphere, which includes glaciers, snow cover, and permafrost. These frozen water reserves at high altitudes are natural responses to stream regulation because they retain precipitation in the form of snow and ice when it is cold and discharge melted water when it is warm. Global warming has, however, changed this balance in a radical way. Cryospheric shifts in the western Himalaya are extensive, with a notable hastening of glacier retreat, diminishing snowfall, and changed melt regimes, also causing a worsening of permafrost. The implications of these changes on the water cycle of the region are far-reaching in terms of its quantity and timing, as in terms of raising the frequency of hazards like glacial lake outburst floods (GLOFs)[20].

3.1. Mass-Balance and Glacial Shrinkage

The glaciers in the western Himalaya are receding back to rates never seen before. Evidence provided by satellite images (e.g., Landsat, ASTER) and aerial inventories, as well as terrestrial measurements, suggests that most regional glaciers are losing mass steadily since the middle of the 20th century. The net balance of glacier mass between accumulation and ablation has turned more negative in the area, with an average rate of loss of 0.3 to 1 meter water equivalent/year (average) being reported, depending on size and location.

Contributors to glaciers receding are:

The air causes the rise in melting glaciers that is experienced, especially during the pre-monsoon and summer seasons.

- Black carbon and dust cover the surface of glaciers, causing a lower albedo that leads to faster melting.
- Changes in precipitation, such as declines in snow and an increase in rain-on-snow.

Debris-free glaciers and small glaciers melt at a higher rate than big glaciers that are covered by debris. Nevertheless, even debrided glaciers are undergoing mass loss at the base, causing them to thin and collapse internally. Glacier recession lowers the buffering capacity of the cryosphere that previously had fulfilled the dry seasonal flow of rivers[21].

3.2. Deteriorating Snow Cover and Altering Patterns of Snowfall Parts

Snow accumulation forms a very important part of the hydro-regime of the western Himalaya, and especially in catchments such as the Chenab, Jhelum and Sutlej rivers. But warmer winters are decreasing snow coverage time, area and depth in most areas of the region.

Major observed changes are as follows:

- Earlier melt snow, a shift in peak flow to occur earlier in the spring.
- Decrease in the snow-covered area (SCA) in winter and early spring as indicated by the MODIS and other remote sensing systems.
- A shift in snow to rain at lower altitudes (2,000–3,000 m) results in a topological runoff at a faster rate instead of a controlled, postponed melt.

Such a loss in snowpack not only changes the timing of streamflow but also the infiltration and in-stream recharge of water, particularly in small alpine watersheds that are dependent on snowmelt-fed springs[22].

3.3. Degradation of Permafrost and Landscape Stability

The esoterically frozen ground, commonly referred to as permafrost in the western Himalaya, is located at high altitudes, especially in Ladakh and in some areas in Himachal Pradesh. Increased temperatures, causing thawing of the ground, are destroying the permafrost, resulting in:

- Glaciers and rockfalls, because the ice-cemented slopes lose their integrity.
- Glaciers destabilize following the weakening of subglacial ice layers.
- Possible emissions of methane and other greenhouse gases trapped under frozen soils, which can aggravate even more the issues of climate change.

Little is known yet about Himalayan permafrost, but its degradation is a long-term risk to infrastructure, ecosystems and water regulation.

3.4. Glaciers, Lakes, and Run-of-River Risk Related to Glacier Lake Outburst Floods (GLOFs)

The recession of glaciers has created glacial lakes and expanded their size in most cases due to damming by unstable moraines. Many of these lakes are increasing quickly in volume, and there is fear of how this will result in Glacial Lake Outburst Floods (GLOFs), which are sudden high-velocity floods whose outcome is the removal of moraine dams.

In the western Himalaya, a few potentially hazardous lakes have been detected by remote sensing as well as field surveys, and they are:

- Shyok basin (Ladakh)
- Zanskar and Chenab valleys
- Glaciers in the vicinity of the Pir Panjal and Zanskar ranges.

The GLOFs' triggers are:

- Rainfall with high intensity,
- Avalanches of lakes of ice or rock,
- Earthquakes,
- Degradation of moraine dams through seepage and meltwater.

GLOFs may cause the worst destruction of downstream communities, infrastructure (roads, bridges, hydropower plants), and ecosystems. Premature alerts and lake stability metrology are significant in reducing the risk of disasters.

3.5. Cryospheric Change Hydrological Implications

Collectively, the scope of glacier ablation, snowpack decline, and permafrost thaw leads to hydrological regime transformation in the western Himalaya:

- **Peak flow shift:** Late summer, when it is dominated by glacial melt, to early spring, when it is dominated by snow melt.
- **Reduced long-term water supplies:** As the glacier storage is reduced, the rivers may one day show low baseflow, particularly over dry seasons.
- **Enhanced flow variability:** There is a growing number of rainfall-driven runoff regimes, which increases the risks of floods and drought.
- **The impact on the recharge of groundwater:** less snow and melting ice on groundwater storage are being affected, which influences the springs and shallow aquifers, which are an important source of water supply in rural areas.

Such shifts threaten the availability of water for security and hydropower generators, irrigation for agriculture, and ecosystem integrity, particularly in locations that do not have high-storage infrastructures or adjustment measures. A brief summary of the cryospheric changes and their profound hydrological impacts is given in **Table 2**.

Table 2. Summary of Cryospheric Changes and Their Hydrological Impacts.

Cryospheric Feature	Observed Change	Hydrological Consequence
Glaciers	Retreat and mass loss	Reduced late-summer baseflows
Snow cover	Decreasing extent and duration	Shift in runoff timing; reduced infiltration
Permafrost	Thawing at higher elevations	Increased landslides and slope instability
Glacial lakes	Expansion in size and number	Higher risk of GLOFs

Awareness of the Cryosphere Cryospheric alterations in western Himalayan glaciers constitute a pressing concern of climatic alteration, with wide-ranging implications to hydrological assets, hazard threats and territorial stability. Becoming familiar with the changes is crucial to being able to predict the future hydrological scenarios and implement the specific adaptation strategy. Ever threatened by the warming already projected by climatic models in the 21st century, the stabilizing effect attributed to the cryosphere within the Himalayan hydrological cycle is becoming an area of high priority for both science and policy [23–25].

4. Alterations in the Hydrological Cycle

The western Himalayas' climate is undergoing significant changes to the hydrological cycle because of the disturbances that have been caused by climate change in changing the temperatures, precipitation, snow, and glaciers' activities. The water cycle in this area has long been balanced between seasonal snowmelt, glacial thaw, monsoon rains, and transpiration. But with the increase in pace of global warming, this balance is getting disoriented, and what we are experiencing is the change in streamflow patterns, the availability of groundwater recharge being erratic, the alteration in the dynamics of soil moisture conditions, and the frequency and severity of hydrological extremes like floods and droughts becoming more common. These changes have major implications for water supply, resource planning, ecosystem operations, and human livelihoods.

4.1. Streamflow and River Discharge Modification

Changes in river discharge patterns are one of the most rapid and monitorable effects of climate change on the hydrological cycle. Mountain rivers such as the Indus, Chenab, Jhelum, and Sutlej of the western Himalaya have traditionally been fed by both snowmelt and glacier melt in addition to monsoonal rainfall.

The major observed and anticipated changes are

- On the earlier actual peak flows that will occur earlier during the spring because there is warmer weather earlier, which causes the melting of the snow earlier.
- The decrease in summer baseflows of glacier-fed rivers with time in the context of glaciers losing mass and contributing less meltwater.
- The enhancement of short-term runoff variability as a result of more intense rainfalls.
- Improved winter flows in certain basins are caused by rain-on-snow occurrences that cause delayed runoff instead of accumulation of snow.

Some catchments might already be facing a higher volume of flows because of higher glacial melt (so-called peak water), which, however, is not a long-lasting condition. Since the volume of the glaciers is still getting smaller, most of the rivers will be in post-peak with reduced discharge, especially during dry months, a scenario that may have serious repercussions on irrigation, hydroelectric power and water supply [26].

4.2. Spring Flow and Recharge of Groundwater

Mountain springs and groundwater are important water sources to rural people in the western Himalayas. Climate change, however, is impacting the amount and time of recharging the groundwater supply.

Important effects:

- Low snow infiltration: As the snow cover dwindles and melts earlier on, less water filtrates into the soil to be used to recharge groundwater supplies.
- Greater surface flow: Heavy rainfall causes the increased surface runoff to move along with the decreased time and chance of infiltration.
- Spring drying and fluctuation: A lot of perennial springs are turning seasonal, whereas some of them are drying out as a whole, especially in middle elevation areas.

The changes are compounded by the modifications in land use, deforestation and soil degradation, further reducing the possibilities of recharge. Recharging is an essential activity since groundwater buffering is a crucial component of drought resilience, and therefore, low recharging is a long-term water security threat in the area.

4.3. Dynamics of Soil Moisture and Evapotranspiration

The terrestrial water balance is also influenced by warmer temperatures and changes in precipitation patterns, by the soil moisture water balance. The warmer temperature is causing an increase in evapotranspiration (ET), which is the overall loss of water due to soil evaporation and plant transpiration; hence, the less water the soil has to provide to crops and plants.

Spotted and anticipated trends:

- Enhanced evapotranspiration, especially during summer and pre-monsoon season.
- Increased soil moisture deficit and thus crop stress, in particular, in rain-fed farming systems.
- Fluctuating patterns of infiltration, owing to heavy precipitation whose duration is brief, exceeding the absorptive rate of the soil.

The dynamics are important to agriculture and to ecosystems and to feedbacks to the atmosphere, which could affect the local climate and precipitation in the form of land-atmosphere interactions.

4.4. Floods and Droughts: Hydrological Extremes

Changes in the water cycle also brought about an increase in the frequency and severity of hydrological extremes, including floods and droughts.

Flood Risks:

- Flash floods and flooding in the riverine areas are caused by the presence of Further intensified monsoonal rains and the occurrence of anomalous acceleration in the processes of mountainous snow/glacier melt.
- Expansion of cities in susceptible valleys and creation of infrastructure publicize people to spill risks.
- The extreme precipitation and geomorphic fragility would promote damming of lands, capable of leading to a sudden flood in the future.

Drought Risks:

- There is an increase in long dry spells, more so during the pre-monsoon.
- Unpredictable rainfall raises uncertainty in agricultural planning and storage of water.
- Weaker spring streams and groundwater levels also contribute towards seasonal water shortages, especially in the mid-hills and trans-Himalaya regions.

These two extreme conditions of floods and drought pose serious problems in terms of water resources management and preparedness in case of disaster.

4.5. Changing Seasonality and Water Supply Planning

The most important process of hydrological change is possibly the seasonal redistribution of water. Customary systems of water resource management in the area have been built around the reliable seasonal periodicities of the flow of water, high water in the summer melt and monsoonal seasons, and low water in the winter.

Nevertheless, there are increases in changes brought about by climate that are:

- Shorter and earlier snowmelt seasons,
- Inconsistent start and ending of the monsoon,
- **Seasonal flow imbalance:** surplus flows in winter and spring, and deficit in summer.

These changes make it cumbersome to plan irrigation routines, hydropower generation, and reservoir regulation. They also test transboundary water treaties and cooperative mechanisms in the region that rely on long-term hydrological predictability.

In a nutshell, global warming is also drastically changing the hydrological cycle in the western Himalaya—in terms of timing, magnitude and reliability of water coming out of the mountains into the plains. The alterations endanger the presence of water, heighten the exposure to flood and famine and put additional stress on pre-existing vulnerable mountain settings and people. The existing trend of hydrological changes warrants a sophisticated insight into developing effective adaptation measures in addition to maintaining effective and sustainable water governance in such a climatically sensitive area [27].

5. Ecosystem and Socioeconomic Implications

Physical changes caused by global warming to the water cycle in the western Himalaya do not remain in the physical environment; rather, these changes extend to the social and ecological set-up of this region. The Himalayan ecosystem, whose stability is already threatened by high gradients, shallow soils and harsh weather, is getting strained by hydrological instability. Similarly, the communities living in these mountain regions (most of whom are dependent on the natural water systems when it comes to agriculture, drinking water, and power) are also becoming more susceptible. This section discusses both ecological and socioeconomic effects of changes in the water cycle, which are interdependent, with the interdependency of the effects presenting complex threats and emerging issues in adaptation.

5.1. Effect on Mountain Ecology and Biodiversity

The western Himalaya encompasses a broad array of ecosystems, like alpine meadows and coniferous forests, temperate broadleaf forests that support diverse life and fauna composed of endemic and endangered species, such as the snow leopard, Himalayan musk deer and several medicinal plants. Seasonal flow regimes and water availability are vital to the structure and functioning of these systems.

Important environmental effects are:

- **Fragmentation of habitat and degradation:** Fragmentation and degradation of habitats, migratory routes and vital habitats.
- **Shifting phenology:** Phenological events, such as the onset and retreat of snow cover and temperature changes, affect the flowering and breeding cycles, and the feeding cycle of plants and animals.
- **Forest dieback and species shifts:** Declining soil moisture and growing evapotranspiration cause reduced stress resilience in forests, predisposing them to forest pests and diseases and invasive flora.
- **Wetland drying:** At higher elevations, wetlands dependent upon glacial meltwater are drying, which affects the biodiversity of the water and flow of migratory birds.

Such ecosystem disturbances may trigger a series of effects, including the loss of ecosystem services like carbon sequestration, erosion prevention, as well as pollination [28].

5.2. Threats to Agriculture and Food Security

Agricultural production in the western Himalaya is mainly rain-fed and spring-fed and thus subject to great variation due to climatic fluctuations and water cycle changes. Smallholder farmers depend on an accurate seasonal water supply to cultivate subsistence crops that include wheat, barley, millet and paddy.

Some of the challenges to agriculture due to climate change are:

- Water shortages during the primary growing periods because of the unstable melting of the snow and drying of the spring.
- Greater droughts and out-of-season flooding threaten crops.
- Reduced production length due to variation in temperature and rainfall patterns.
- Less soil fertility, stress on moisture caused by high rainfall and an enhanced rate of evapotranspiration.

The diminished agricultural production will directly challenge both food security and profitability, particularly in remote areas without easy access to markets or irrigation systems. Workloads tend to be heavier among women because they have to travel long distances to acquire water and deal with changing agricultural seasons.

5.3. Community Resilience and Drinking Water Access

Springs and small streams are the most common source of drinking water in most areas of the western Himalayas, particularly in the mid-hills and trans-Himalayan regions. Groundwater sources are becoming increasingly scarce as bodies of water are drying up as a result of deteriorating groundwater recharge and alteration of the patterns of precipitation.

The consequences to society are:

- More burdens related to fetching water, especially by women and children.
- The effect of water stress on the mobility of households is leading to the abandonment of villages.
- Water wars, particularly during dry months or seasons of wild extremes.

A wider threat to water supply infrastructure is seen in the form of seasonal water shortages, even in urban areas like Shimla and Srinagar [29].

5.4. Hydro Impacts–Hydropower and Energy Security

Hydropower is a principal pillar of the local development in the western Himalaya, in which several medium-sized and large-scale dams have been or are under construction in rivers like the Sutlej, Beas, and Chenab. Such projects are reliant on streamflows that are predictable and baseflows comprised of snow/glacier melt.

Some effects related to climate are:

- **Decreasing flow reliability:** There is a risk of long-term glacier retrenchment leading to decreasing flows during the dry season, thus diminishing generating capacity.
- **Extreme event damage:** Damage can be inflicted by cloudbursts, landslides, and GLOFs on dams, turbines, and the transmission system.
- **Water distribution wars:** Changing flow patterns may impact downstream water distribution agreements between states or nations (e.g., the Indus Waters Treaty between India and Pakistan).

The hydrological uncertainty in supply is not only threatening the economic returns but also the grid and long-term planning.

5.5. Migration, Livelihood Stress, and Social Vulnerability

Climate change is causing hydrological stress in some villages, leading to rural distress and outmigration. With the unviability of agriculture and the depletion of water sources, families are moving to towns and cities in search of livelihood opportunities, with the youth being the worst victims.

Associated trends:

In Uttarakhand and sections of Himachal Pradesh, entire communities have moved, and there are an increasing number of what are known as ghost villages.

- Cultural dislocation has been experienced as those cultural practices involving traditional mountain knowledge and community-managed water systems (e.g., kul, naula, zabo) are being lost.
- Increased insecurity of underprivileged communities in society, like lower castes and women, whose representation remains minimal in water governance.

This movement not only depopulates vulnerable mountainous landscapes, but it also overloads the infrastructure in the downstream city [30].

5.6. Transboundary and Regional Implications

Western Himalaya rivers flow through several national boundaries, and management of these rivers is a challenge of transboundary water management. Disruptions in the water cycle can:

- Fuel geopolitical disputes concerning common rivers (e.g. Indus basin between India and Pakistan).
- Subvert existing water treaties that are founded on records of long-term past flows that are currently changing.
- Impact on downstream food and energy security within the Indus and Ganges basin.

In the face of these emerging challenges and in the interest of establishing water diplomacy within a region, cooperation, sharing of data, and engaging in joint research are important.

The effects of climate-induced changes in the water cycle in the western Himalaya are complex as they cut through ecological integrity, agricultural productivity, societal health, energy security, and social cohesion. The impacts are usually experienced most by vulnerable groups of people and susceptible ecosystems, and hence, climate adaptation and resilience-building should be integrated into regional development planning. It is critical in attaining a sustainable and equitable future to have a clear understanding of the social-ecological connectivity of the Himalayan water system [31–33]. Socioeconomic impacts of such hydrological changes are briefly tabulated in **Table 3**.

Table 3. Ecosystem and Socioeconomic Impacts of Hydrological Changes.

Sector / System	Key Impact
Agriculture	Reduced irrigation reliability; crop failure risk
Drinking water	Drying springs; reduced access in rural areas
Hydropower	Unpredictable streamflow; infrastructure risk
Biodiversity	Habitat shifts; alpine wetland loss
Migration	Outmigration due to water and livelihood stress

6. Monitoring and Modelling of Hydrological Changes

Monitoring and modelling play an essential role in the realization of the dynamic alteration of hydrological studies in the western Himalaya due to global warming. Since the region is ecologically complex, with steep topography and sensitive to climate change, water resource planning, disaster risk reduction, and climate adaptation require strong observational systems and predictive capability. The western Himalaya, however, is one of the most data-scarce and observation-demanding mountains on the globe. In this section, the author reviews the situation concerning the existing hydrological observations, the developments and shortcomings of the modelling approaches, and the outstanding issues in data acquisition that make it difficult to comprehend and address the issues of water cycle alteration in the area as a whole.

6.1. Weaknesses of the Current Monitoring Infrastructure

The western Himalaya has a limited number of hydrometeorological stations, difficult terrain, poor access, extreme weather conditions and political sensitivity in international regions, making it hard to conduct monitoring of the hydrometeorology in the region. Most weather and discharge stations are present at lower levels; this gives little information concerning the processes at the higher levels that involve snow and glacier melt, which feature a lot in the hydrological equilibrium.

The major problems to be considered are:

- **Scarcity of high-altitude observations:** Only six stations above 3,000 meters; this underestimates important cryospheric processes, including accumulation and melting of snow, runoff by glaciers, and permafrost.
- **Inconsistent time series:** Discontinued records and data omissions are counter-productive in long-term trend analysis and model calibration.
- **Inadequate quality of spatial coverage:** Ground observations are not equally distributed in the river basins, with wide gaps that leave important sub-catchments with outstanding data.

Floods, landslides and GLOFs are equally uncertain with early warning systems, which have been further plagued due to the lack of in-situ data to predict and respond to effectively [34,35].

6.2. Remote Sensing and Satellite Monitoring Development

To curb constraints on the ground, remote sensing technologies have gained significance as a way of monitoring hydrological variables throughout the Himalaya. The data presented by satellites is spatially large, repeated and in many cases, real-time data on numerous facets of the water cycle presented by satellites.

Important uses include:

- **Snow cover and snowmelt:** Snow-covered area (SCA) can be estimated using MODIS, Sentinel-2, and Landsat imagery, and so can the duration of snow cover.
- **Glacier dynamics:** Optical and radar instruments (e.g., ASTER, Sentinel-1, ICESat-2) are used to monitor glacier retreat and variations in the surface velocity and thickness.
- **Glacial lakes:** Stratospheric water balance: The extent of Surface Water extent: SAR (Synthetic Aperture Radar) and optical imagery can be used to detect glacial lakes as well as flood inundation zones.

Soil moisture and evapotranspiration: The SMAP and MODIS sensors will report regional estimates of soil moisture and evapotranspiration by vegetation. Although satellite data cannot be neglected, it may need ground truthing to be accurate, and the workability of satellite data may be constrained by cloud cover, ground spatial resolution and terrain shadowing.

6.3. Climate and Hydrological Modelling Activities

Modelling is essential in the determination of present and future hydrological conditions based on the development and forecasts of climate scenarios. Network researchers build hydrological and glacio-hydrological models to simulate river discharge, snow and glacier melt, and extreme events (e.g., SWAT, HBV, VIC, PRMS, GLOFAS, SPHY, Snow Model).

The main modelling activities are aimed at the following:

- Generation of runoff and streamflow predictions with climate change (e.g., RCP 4.5, RCP 8.5).
- Glacier contributions to river flow, which aided in the calculation of when a basin might be at its peak water level.
- Forecasting of floods and mapping of flood risk areas, particularly in the flood-prone basins such as the Sutlej and Jhelum.
- Analysis of water balance on multiple scales of space and time.

Strengths:

- Models can assist in testing what-if scenarios and guiding projections of long-term glacier loss and changes in precipitation.
- Cryosphere, hydrology, and climate data are integrated in the models, and this enables multi-sectoral planning.

Limitations:

- Large model uncertainty since there were only a few input data points and calibration of the parameters.
- Inability to represent complex terrain, microclimates and heterogeneity of land use.
- Scaling: Models can perform poorly at a sub-watershed level (or community level), whereas they perform well at the basin scale.

6.4. Ambiguity and Missing Data

Major problems in Himalayan hydrology include uncertainty due to incomplete information and flaws in methods. The major uncertainties are:

- The future role that glaciers will play towards river flows as they diminish.
- Snow, ice and rain interactions in transition elevation zones.
- The flow of groundwater is poorly researched in a mountainous landscape.
- The effects of water infrastructure on a small scale (e.g., check dams, tunnels) on regional flow regimes.

Such uncertainties limit the confidence given to historical evaluations as well as projections into the future, and this necessitates:

- Other high-elevation surveillance posts;
- Institutional and cross-border sharing of open-access data.
- Cross-disciplinary research across climatologists, glaciologists, hydrologists and social scientists [36,37].

Key gaps include: (1) Limited high-altitude groundwater data, (2) Discrepancies in glacier contribution estimates, and (3) Policy fragmentation across Indus/Ganges basins.

6.5. Communal Monitoring and the Place of Citizen Science

Over the last few years, community-based monitoring activities have become an important tool in addressing data gaps, especially where the sites to be covered are located in isolated communities. Simple hydrometeorological monitoring can be done through local communities that have been trained at the local level:

- Spring includes discharge and timing,
- Quantities and patterns of rainfall,
- Observations of snowfall at definite altitudes.

Such citizen science projects not only increase data collection, but also create local water knowledge and ownership. For example, scientific tools, as well as traditional knowledge, have been incorporated into projects such as Spring Revival and Himalayan Adaptation, Water and Resilience (HI-AWARE).

Hydrological changes in the western Himalaya are monitored and modelled, but are currently still limited by the complexity of the terrain, lack of infrastructure, and absence of adequate data. Although remote sensing and models are capable of providing potent tools in deciphering changes in the water cycle, the efficiency of such tools is impaired by ground validation inadequacy and institutional partitioning. Monitoring networks need to be more heavily invested in, data systems need to be more integrated and collaborative modelling needs to be built, to aid scientific research and policy-making alike in water governance and overall resilience. The reinforcement of these systems will play an instrumental role in manoeuvring through the water problems of a warming Himalaya [38].

7. Adaptation and Mitigation Strategies

The accelerating effects of global warming on the water cycle in the western Himalaya are creating a potential need to prioritise and implement situation-differential adaptation and mitigation measures. While mitigation is directed at reducing greenhouse gas emissions and lessening global climatic change, adaptation is directed at system readjustments and practices to face the moderated changes and more. Because of the ecological sensitivity of the region, its geographic isolation, and relative negligence and vulnerabilities of its socio-economic status, there should be the use of a dual track approach that is composed of top-down planning and grassroots innovation. In this section, the authors discuss the status and capacity of the adaptation and mitigation efforts, institutional machinery and gaps that still need to be filled to increase resilience in the western Himalaya.

7.1. Water Management That is Climate Resistant

Adaptation to hydrological change starts with climate-smart planning of water resources. This includes enhancing the more efficient, reliable, and equitable utility of water in anticipation of more seasonal and interannual variations.

Important strategies include:

- **Watershed-based planning:** The planning of water over the basin or sub-basin level to maximize usage, recharging, storage and distribution.
- **Spring-shed management:** Rehabilitation and protection of Himalayan springs through recharge area protection, runoff management and reforestation of spring catchments.
- **Water storage and harvesting:** Building or refurbishing conventional (e.g., qanats, kul, guls) and innovative rainwater storage infrastructure to absorb droughts.
- **Demand-side policies:** Resource-efficient irrigation (drip, sprinkler), crop diversification and community-level water budgeting.

These methods not only solve the water security problem but also unload pressure on the dwindling glaciers and groundwater sources [39].

7.2. Disaster Preparedness and Early Warning Systems

The rise in the occurrence of glacial lake outburst floods (GLOFs), flash floods, and landslides necessitates the inclusion of a better risk monitoring and response system.

Priority actions:

Installation of early warning systems (EWS): The installation of sensors, cameras, and communication networks to keep track of glacial lakes, rainfall, river levels, and landslide-prone slopes.

- **Community-based disaster mitigation:** Educating residents about evacuation exercises, mapping of hazards and first aid.
- **Zoning and land use planning:** Putting risky zones and limiting the creation of infrastructure in areas at risk (e.g., riverbanks, unstable slopes).
- **GLOF risk mitigation engineering:** The management of outflow of glacial lakes, the reinforcement of moraine dams, and the establishment of buffer zones laterally.

Coordination of response agencies of disaster management, research institutions, and local governments is central to the establishment of solid early warning and response systems.

7.3. Adaptation Through Ecosystem-Based Adaptation (EbA)

Ecosystem-based Adaptation focuses on restoring and sustaining natural ecosystems in a bid to establish strength against the effects of climate change.

Examples of EbA in the Himalaya:

- Catchment reforestation and afforestation to enhance infiltration, suppress runoff and control slope stability.
- The protection of alpine pastures to stop overgrazing and preserve the ability of the water-retentive high-altitude meadows.
- Preservation of the wetlands to absorb floodwater, recharge the underground water reservoirs and also preserve their biodiversity.
- Agroforestry practices with mixed crops of trees and crops to have diversified livelihoods and soil moisture conservation.

An additional benefit of EbA is that there is an added benefit regarding biodiversity, carbon sequestration, and other co-benefits, including fuelwood and fodder.

7.4. Reinforcing Policy and Institutional Structures

Efficient adaptation will entail harmonious policies, robust institutions and decentralised, responsive systems of governance.

Recommended reforms to the institution:

Mainstreaming of climate adaptation in water and land use policies, rural advancement programs, as well as disaster risk reduction strategies.

- Community participation and decentralisation, increasing the powers of village councils and user groups in water management and ecosystem management.
- Transboundary collaboration in the case of rivers that are shared by each country, between India, Pakistan, China, and Nepal, so that there is coordination of data sharing and water management.
- Institutionalization and mobilization of climate finance, accessing international funding (e.g., Green Climate Fund, Adaptation Fund) for infrastructure, livelihoods and research.

To ensure adaptation is interlinked with wider development agendas, water, energy, agriculture, and environmental departments should be coordinated across sectoral lines [40].

7.5. The Significance of Traditional Knowledge and Community Practices

The Himalayan Mountain populations have traditionally evolved highly resilient building blocks of water and land use in response to the climatic variability prevailing in the region. Combining local knowledge that is revived and incorporated with scientific devices is likely to increase the local adaptation ability.

Notable practices:

- Gravity-irrigation: (kul, guls in Himachal and Kashmir, zabo in Nagaland).
- They use glacier grafting, where they grow man-made ice reservoirs to irrigate in late seasons.
- Native systems of prediction, using animal behaviour, cloud formations and vegetation indicators.

The social water governance, including the Paani panchayats or the community water management committees. These practices can be documented, preserved and adapted to provide cost-effective and culturally based ways of addressing the new climate issues.

7.6. Low-Carbon Advancement and Mitigation Strategies

Although adaptation is the most urgent concern for the region, mitigation activities are important to reduce the long-term risks of adverse climate change.

Important lines of climate mitigation:

- **Clean energy shift:** Switching usage of diesel and firewood with solar energy, micro-hydropower, and biogases.
- **Sustainable tourism:** To encourage an eco-tourism framework to be used that reduces waste, emissions, and consumption of water within sensitive alpine areas.
- **Carbon sequestration:** planting trees in the community forests.

Low-emission agriculture: Promoting the use of organic agriculture, composting, and tillage.

Such actions yield significant co-benefits, including enhanced air quality, healthier ecosystems, and improved livelihoods. To effectively adapt to shifts in the western Himalayan water cycle, a holistic, inclusive, and multi-level approach is essential—one that integrates technological innovation with traditional and religious knowledge systems. Ranging from spring revival and glacial lake surveillance to agroecology and decentralised governance, the range of options for adaptation is being tried and tested and scaled up across the region. Simultaneously, success in long-term resilience depends on mitigation efforts beforehand, cross-border collaboration, and prolonged investment in the construction of climate-resilient infrastructure and establishments. It will be of utmost importance to have a coordinated effort to synergise scientific research, action by the community and policy change to give the Himalaya and the downstream dependents a sustainable future [41–43].

Future work should aim to develop a comparative analytical framework that distinguishes the Western Himalaya's climate-resilience dynamics from the Central and Eastern Himalayas, highlighting policy successes and bottlenecks unique to each sub-region.

Such differentiated insights can serve as a foundation for benchmarking regional policy effectiveness, particularly concerning spring revival, glacial monitoring, and transboundary governance structures.

8. Conclusions

The western Himalaya is experiencing profound changes in its water cycle due to the rapid impacts of global warming. Rising temperatures, shifting precipitation patterns, and cryosphere degradation are altering the region's hydrology, leading to unpredictable consequences. Glaciers are retreating, snow cover is declining, and rainfall variability is disrupting river flows, groundwater recharge, and soil moisture, while intensifying floods and droughts.

These changes pose severe ecological risks, threatening biodiversity and fragile mountain ecosystems, while also undermining water security, agriculture, energy production, and public health—particularly for vulnerable communities dependent on snowmelt and springs. Despite progress in remote sensing and modeling, critical data gaps persist, especially in high-altitude zones, limiting effective policymaking. Enhanced monitoring, improved climate projections, and cross-border data sharing are urgently needed.

Adaptation strategies—such as watershed management, spring revival, early warning systems, and ecosystem-based approaches—must be prioritized, integrating traditional knowledge with modern science. Stronger institutional frameworks, transboundary cooperation, and climate financing are essential to building resilience.

As a frontline of climate change, the western Himalaya's stability is crucial not just for local populations but also for downstream water security and regional climate balance. Proactive, collaborative, and science-driven action is imperative to safeguard this critical mountain system and the millions who depend on it. Future research must adopt transdisciplinary approaches, linking cryospheric, hydrological, and social dynamics to develop sustainable solutions.

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Conceptualization, F.C. and Y.Y.; validation, F.C. and Y.Y.; formal analysis, F. C.; investigation, Y.Y.; resources, F. C.; data curation, Y.Y.; writing—original draft preparation, F.C. and Y.Y.; writing—review and editing, F.C. and Y.Y.; visualization, F.C. and Y.Y.; supervision, F.C.; project administration, F. C.

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The authors declare no conflict of interest.

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