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Climate Change, Glacier Retreat, and Water Security in Ladakh: Current Status, Challenges, and Future Perspectives

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Abstract

The cold, dry, high-altitude region of Ladakh in the Indian Himalaya relies nearly entirely on water from glaciers and snowmelt - hence its inclusion among the more climate-sensitive parts of the region. The combination of these effects—warming, changing precipitation, melting glaciers, shrinking snowpack and the increased frequency of extreme weather events—is altering the water balance in the area and threatening water security for the future. It has consequences that are enormous to say the least: access to drinking water, agriculture, groundwater recharge, healthy ecosystems, and livelihoods in the mountains. This review reflects the current state of knowledge on climate change and glacier retreat in Ladakh, and the implications for water security, based on peer-reviewed research and international assessment reports, as well as regional studies. This provides information on the observed climatic trends, glacier and cryosphere dynamics and the potential impacts on streamflow variability, water availability at seasonal timescales, groundwater, water quality and social resilience. Also covered are adaptation measures currently being implemented, including traditional ecological knowledge, artificial glaciers and ice stupas, integrated watershed management, climate smart agriculture and use of geospatial tools for water planning, while noting where the evidence base is weak, such as in the scarcity of long-term hydro-meteorological records, uncertainty in glacier and hydrological modelling and the focus on only a handful of adaptation measures in limited future climate scenarios. If water systems in Ladakh are to remain viable then strengthening climate-resilient water governance, including integrated cryosphere–hydrology monitoring, community-based climate adaptation, ecosystem restoration and evidence-based policy, will be essential, with lessons to be learned all throughout the Hindu Kush Himalayan region.

Keywords: Climate change, Glacier retreat, Water security, Ladakh, Cryosphere, Himalayan glaciers, Water resources, Climate adaptation.

Introduction

The Hindu Kush Himalaya (HKH) – also known as the "Third Pole" – is home to the world's largest repository of non-polar snow and ice, and provides freshwater to nearly two billion people throughout Asia (Bolch et al., 2019; Immerzeel et al., 2020; IPCC, 2021; Yao et al., 2022). Like a seasonal bank account, winter precipitation in its cryosphere is stored as snow and ice, which are then released as meltwater during the dry summer months, and which is returned to regulating streamflow, groundwater recharge, ecosystem function and agricultural productivity. But anthropogenic warming has disrupted that equilibrium, leading to glacier retreat, various changes in snow dynamics and greater hydrological variability across the HKH that affects water security and sustainable development (Huss & Hock, 2018; Kraaijenbrink et al., 2017; Yao et al., 2022).Ladakh, nestled in the northwest Indian Himalayan region, stands out as one of the most climate sensitive regions of the HKH, thanks to its high elevations, sparse vegetation cover and low amount of rainfall. Annual precipitation is less than 100 mm over much of the area and snow is the only source of precipitation in the region, with western disturbance bringing about 80 – 90 % snowfall during winter, while the Indian summer monsoon gives only around 10% (Dimri et al., 2015; Bolch et al., 2019). Glaciers and seasonal snowpack are thus not one of the various sources of water but are the main water body that sustains domestic water consumption, agriculture and livestock, wetlands, and a rapidly expanding tourism industry. However, unlike other, monsoon-fed river basins in India, rivers in Ladakh rise and fall based on climate-induced fluctuations in glacier and snowmelt timing and magnitude, and such fluctuations cause this region to be particularly vulnerable to climatic variations (Immerzeel et al., 2020; IPCC, 2021).

In the Himalaya, the warming over the past decades has also been more pronounced than the global average, referred to as elevation dependent warming (Pepin et al., 2015; Palazzi et al., 2019). The snow cover season has been reduced, and the ablation rate of glaciers has been increased by the rising air temperature, which has led to destabilisation of the permafrost and increased precipitation as rainfall, particularly at lower altitudes (Azam et al., 2021; IPCC, 2021). Concurrently, the changes in the South Asian climate circulation and the increased spatial and temporal variability of western disturbances have disrupted the space and time pattern of snowfall (Dimri et al., 2015; Bolch et al., 2019). All these are contributing to very quick changes in the hydrology of the whole region through the cryosphere.

The most noticeable sign of this change is glacial retreat. Glacier coverage, ice debris-covered and thinning, and ice mass overall loss, as observed by remote sensing and fieldwork, are consistent in many glacier catchments, though again the overall picture is not uniform as it is influenced by glacier morphology, debris cover, glacier topographic and climatic setting (Gardelle et al., 2012; Azam et al., 2021; Bhambri et al., 2013). Short-term this extra acceleration in melting will cause an increase in river discharge but this increase is only temporary. Beyond the 'peak water', the water provision by glaciers will decrease further with ongoing melt until it reaches a certain sediment supply threshold, and dry-season streamflow will start to decline on the long-term (Huss & Hock, 2018; Immerzeel et al., 2020). This transition is a serious issue for communities whose irrigation relies on glacier-melt, which they need to arrive and become available on a consistent basis year-on-year.

Impacts extend beyond hydrology. The agriculture of Ladakh is some what completely dependent on glacier sources for water, through local channels called yuras, which feed mainly on barley, wheat, pea and horticulture. Increased climatic variability, decreasing glacier storage, and reduced supply due to earlier snowmelt have disrupted irrigation planning, reduced productivity, and intensified seasonality of water availability (Nüsser et al., 2012; Schmidt & Nüsser, 2017). The same time, urbanisation, tourism, new infrastructures and population growth are exerting increased pressure on the finite water resources. Ecologically, altered flow regimes are not just impacting alpine wetlands and biodiversity but they also increase the risk of glacial lake outburst floods (GLOFs), flash floods, landslides, and sediment transport (Shugar et al., 2021; IPCC, 2021).

But Ladakh has also become a somewhat global model region for climate adaptation through community initiatives. In the field of water management, various modifications to supply water have proven to be highly successful, including Indigenous water-management systems, artificial glaciers, Ice Stupas, traditional ecological knowledge and integrated watershed management (Nüsser et al., 2019; Wangchuk, 2014). But whether these interventions can keep up with ongoing warming, is an open question – one that suggests the need for integrated approaches that involve the monitoring of the cryosphere, climate modelling, groundwater management, hydrological assessment, remote sensing and policy interventions.

There have been numerous articles written on the glaciers in Ladakh, its hydrology, its climate and the management of water in it — all of which are spread out in disciplines. Relatively few reviews include a coherent discussion of the interrelatedity and interplay of climate change, glacier retreat, water security, ecological impact, adaptation, and research priorities. The synthesis is what decision-making and water governance for climate resilience require.

This review aims to deliver this: critically examining the current knowledge on climate change and glacier changes in Ladakh; mapping the implications for water security in the region; examining the ecological and socio-economic consequences of glacier changes; summarising existing approaches on how to adapt; identifying key knowledge deficits, and pinpointing potential avenues for future research.

Climate Change Trends in Ladakh

Climate plays an undue influence on glacier mass balance, snow accumulation, streamflow and water availability in general in a high altitude cold arid region like Ladakh. Precipitation in Ladakh is dominated by winter western disturbances and is predominantly received during winter whereas in the monsoon-dominated central Himalaya, it is mainly received during the monsoon season, thus providing the glaciers with accumulation and freshwater recharge during the winter season (Dimri et al., 2015; Bolch et al., 2019; IPCC, 2021). This dependence results in disproportionally large impacts of changes in regional hydrology and water security in response to relatively small temperature and winter precipitation changes (Immerzeel et al., 2020).

Windward Himalaya has a strong elevation dependent warming signal, as clarified by meteorological records, with an increase in temperature that has been higher in the north west Himalaya than the global mean in the past few decades. Minimum temperatures have increased, especially during the winter months, leading to a shorter snow cover season, higher glacier summer melt rates and less initial snow cover. The majority of this can be attributed to a combination of snow-albedo feedback, alterations in atmospheric circulation and increased longwave radiation (Pepin et al., 2015; Palazzi et al., 2019; IPCC, 2021; Azam et al., 2021).

The precipitation has become more erratic as well. Total annual precipitation is still low – in many valleys below 100 mm – but this has altered significantly in terms of when and how the precipitation occurs in the form of snow. The warmer winter results in the increased fractions of that precipitation falling in the form of rainfall, reducing seasonal snow storage and diminishing glacier mass balance and streamflow during the summer (Dimri et al., 2015; Bolch et al., 2019). Water availability is further complicated by interannual fluctuations in western disturbances, and subsequent impacts for agriculture and rural livelihoods (Shea et al., 2015; Immerzeel et al., 2020).

This is accompanied by an increase in the occurrence of the region's hydro-meteorological extremes due to climate change. The 2010 Leh cloudburst set a fine example of how the high altitude landscapes can be at risk from short duration/intensity precipitation events able to cause flash floods, debris flows and damage to infrastructure (Thayyen et al., 2013). With further warming of the atmosphere, moisture retaining capacity also rises — leading to more of these extreme events as well as the melting of glaciers and growing of glacial lakes (IPCC, 2021, and Shugar et al., 2021).

Projections have virtually no ambiguity that warming will persist throughout the 21st century, under all of the Shared Socioeconomic Pathways (SSPs) considered. In the Hindu Kush Himalayas glaciers, even the lower emission scenarios indicate significant ice loss, with scenarios under higher levels of emissions potentially resulting in ice loss of more than 50% in a number of glacierised basins by the end of the 21st century (Kraaijenbrink et al., 2017; Bolch et al., 2019; IPCC, 2021). As the region shifts towards a loss of peak water, dry-season meltwater will gradually decrease and have long-term implications for water security (Huss & Hock, 2018; Immerzeel et al., 2020).

All these trends confirm one thing – the climate is changing rapidly in Ladakh and the contributions of the cryosphere, the region's hydrology, and to its ecosystems are, in their entirety, to be explored in the next section (Azam et al., 2021; Bolch et al., 2019; IPCC, 2021)

Glacier Retreat and Cryospheric Changes

Ladakh's cryosphere (glaciers, winter snow cover, permafrost, glacial lakes and ice-covered areas) together act as its water bank, which stores the winter precipitation and releases the water in a trickle during summer. It is being degraded and losing its extent throughout the Indian Himalayas due to rising temperatures, related to climate change, decreasing snowfall, altered precipitation patterns and due to human pressures. Glaciers of different altitudes, aspects, debris cover and morphology show a wide variety of glacial response but the common feature in most of them is that the glaciers have a negative mass balance and a steady retreating trend across most of Ladakh (Bolch et al., 2019; Azam et al., 2021; IPCC, 2021).

Glacier Distribution and Characteristics

Within the region, there are numerous glaciers, predominantly valley types strewn across Karakoram, Ladakh, Zanskar and eastern Himalayan segments of the region and maintained primarily by winter snow in the form of western disturbance flow (Bolch et al., 2019; Dimri et al., 2015). Due to the dry climate in the region, these glaciers gain less mass per year than the glaciers further East that receive their snowfalls during the monsoon season, giving them a higher sensitivity to changes in the amount of winter snowfall and changes in summer temperature (Gardelle et al., 2012; Azam et al., 2021).

Not all glaciers are alike. The surface coverage of thick debris insulates the underlying glacier ice, and also slows down surface melt rate, while glaciers with clean-ice surface cover are highly sensitive to atmospheric warming (Scherler et al., 2011; Bolch et al., 2019). The impact of warming on a specific glacier can also depend on variables like elevation, aspect, glacier size, and topographic shading, resulting in varying retreat rates between adjacent glacier systems (Bhambri et al., 2013; Azam et al., 2021).

Evidence of Glacier Retreat

It is clear from satellite imagery, aerial photographs and field observations that glaciers in Ladakh have undergone significant glacier retreat over the last few decades. Using remote sensing, the changes in glacier area, length and thickness have been monitored across the northwestern Himalaya, except in one region. Gardelle et al. (2012) and Bolch et al. (2019), as well as Bhambri et al. (2013), reported the 'Karakoram Anomaly' which indicates that some glaciers of Karakoram have been stationary or even enjoyed mild expansion.

With the exception of this anomaly, all the ranges in the Ladakh and Zanskar exhibit continued receding. Landsat, Sentinel, ASTER and high-resolution elevation models show that accumulations areas have decreased, termini have retreated and glaciers are increasingly fragmented over the past four decades (Azam et al., 2021; Bolch et al., 2019). Small glaciers in low lying areas – areas with already limited accumulation potential – have decreased more rapidly (Kraaijenbrink et al., 2017; IPCC, 2021).

Fieldwork also reveals the decreasing ice thickness and the increase of ELA, which are indications of consistent negative mass balance. This recession is likely to keep going with warming over the 20th century, especially under high emission scenarios (Huss & Hock, 2018; Immerzeel et al., 2020).

Glacier Mass Balance and Melt Dynamics

Mass balance is the difference between mass accumulation due to snow precipitation and mass loss due to melting, sublimation and calving. As summer temperatures rise and a reduction in winter precipitation slowly occurs across Ladakh, the balance is now firmly negative (Azam et al., 2021; Bolch et al., 2019). This correlation between less snow and lower albedo can also lead to earlier exposure of lower albedo glacier ice, so allowing it to absorb more incoming solar radiation, further accelerating ablation and potentially prolonging the melt season (Pepin et al., 2015; IPCC 2021).

This process is well documented and has an arc. The first effect of melting is the increase streamflow (peak water phase), followed by a temporary increase in meltwater discharge above historical averages. However, when glaciers reach a critical level of volume, glacier meltwater production begins to decrease despite the ongoing warming, as well as the province's dry-season river flows (Huss & Hock, 2018; Immerzeel et al., 2020). Perhaps, that's the greatest long-term challenge for water security in the glacier-fed areas such as Ladakh.

Snow Cover and Permafrost Degradation

Seasonal snow cover is more than just pretty—it helps to regulate surface albedo, soil temperature, groundwater recharge and timing of spring runoff. Warmer temperatures have already reduced snow season and advanced snow melt by weeks in many catchments of the Himalayas (Bolch et al., 2019; IPCC, 2021) resulting in earlier exposure of glacier ice and further accelerating melt.

One which has yet to be investigated to the same degree is permafrost degradation. Ice rich slopes become less stable as the ground starts to thaw, increasing the risk of landslides, debris flows, and rockfalls, as well as changing the routes of water flow through the ground (Gruber & Haeberli, 2009; Bolch et al., 2019). Monitoring of permafrost in a systematic way is largely lacking in Ladakh, but available information indicates a progressive increase in the geomorphological instability, with impact to the infrastructures and water resources.

Black Carbon and Cryosphere Degradation

Warming air isn't the only thing melting Ladakh's glaciers. Light absorbing aerosols (LAA), including black carbon (BC), from biomass burning, fossil fuel combustion, industry and vehicle exhaust darken the snow and ice surface and increase its solar absorption which leads to greater melt (Bond et al., 2013; Ramanathan & Carmichael, 2008).

However, numerous studies have examined the impact of black carbon as an important non-climatic factor influencing glacier melt in the Himalaya in addition to warming air temperatures (Bond et al., 2013; IPCC, 2021). The increase in tourism and road construction, as well as vehicle exhaust in the region and the presence of military activity in the area, could potentially be contributing to the regional aerosol loading, but systematic data is still not available for the region.

Expansion of Glacial Lakes and Emerging Hazards

Retreating glaciers have created and been creating proglacial lakes throughout the Himalaya, many of which are dammed by unstable moraines. Failure of those dams can lead to a devastating Glacial Lake Outburst Flood (GLOF) (Shugar et al., 2021; Bolch et al., 2019). The risk of major slope movements, which may cause flooding downstream, is increased by permafrost degradation.

Finally, although the number of large glacial lakes is at present less in Ladakh compared to the eastern Himalaya, Glacier Observed Lake Outburst Floods (GLOF) are likely to be at higher risk in several catchments with increasing glacial retreat. What is needed for disaster risk reduction here will include better remote sensing, hazard mapping, early-warning systems, and continuous monitoring at the field level (Allen et al., 2019; Shugar et al., 2021).

Implications for Water Security

In other words, the cryospheric degradation is altering the hydrology of Ladakh. Declining glacier volume, declining snow storage, increasing evapotranspiration and changing timing of melt water all reduce the availability of freshwater in the growing season. Streamflow, groundwater recharge, irrigation scheduling, ecosystem function and domestic water supply are all subject to uncertainty owing to glaciers retreat (Immerzeel et al., 2020; Huss & Hock, 2018). Continued monitoring of the cryosphere, coupled with climate modelling, hydrological studies and community adaptation, will be necessary to stay up with these changes.

Impacts of Climate Change and Glacier Retreat on Water Security

Water security is not only the supply of water – it is the sustainable provision of water that is abundant, of good quality, safe, reliable and available for people, ecosystems and economic activities. In Ladakh that security is in fact bound with the cryosphere, either glaciers or seasonal snowpack, which are natural reservoirs sustaining the flow through the otherwise dry long stream season. This storage system is affected by the alteration of water availability in all domain sectors due to glacier retreat, decreasing snowfall and increasing hydroclimatic variability under changing climate (Immerzeel et al., 2020; Huss & Hock, 2018; Bolch et al., 2019).

Altered Hydrological Regime and Streamflow Dynamics

The glacier-fed rivers are the major sources of fresh waters in Ladakh with the streams running through spring and summer seasons when rainfall is negligible. Glacier melt has increased with warming, leading to increased discharge in the summers in many catchments as a transient meltwater peak, but as glacier volumes dwindle beyond this peak, streamflow decreases (Huss & Hock, 2018; Immerzeel et al., 2020). Going forward, the availability of water is becoming more and more unclear, particularly at the end of the summer and fall when the demand for irrigation is still high but glacier melt is diminishing.

There is also earlier snowmelt, as runoff is now received weeks earlier in the season than usual. That mismatch leads to a reduction of water supply at the critical times in the farming year and also an undermining of irrigation systems which are designed for the more predictable climate (Barnett et al., 2005; Bolch et al., 2019; IPCC, 2021).).

Agricultural Water Insecurity

This all-important farming is in each case carried out in Ladakh using glacier-fed yuras channels that convey meltwater from a mountain stream into terraced fields. Barley, wheat, buckwheat, peas and horticultural crops all require consistent irrigation during limited periods of crop growth. Glacier storage decreases, melting speed delays and the decrease of snow cover has a combined effect resulting in higher irrigation uncertainty, shorter growing seasons and lower productivity in several valleys (Nüsser et al., 2012; Schmidt & Nüsser, 2017; Dame & Nüsser, 2011).

The variability in the climate has also affected competition between villages regarding limited irrigation water supplies, with more upstream villages suffering in comparison with those downstream. There is increasing pressure on traditional water-sharing systems as discharge levels have been reduced, growing practices have changed and cropland surface areas have grown. Some communities have reacted to this by switching to less water-consuming crops and relying more on groundwater, although this is less well known in most parts of Ladakh (Nüsser et al., 2019, Bolch et al., 2019).

Drinking Water Availability and Urban Water Stress

The town of Leh and surrounding areas have developed at a rapid pace in the last 10-20 years, and so has the demand for domestic water in this part of the country. The glacier-fed supply systems are subject to high stress due to population growth, tourism, rising standards of living and new infrastructure projects (Schmidt & Nüsser, 2017; Müller et al., 2020. Seasonal water shortage is a common occurrence in many of the settlements, especially in early spring, when snowmelt is at peak and during low recharge from inflows of groundwater.

Climate change exacerbates all this by making springs less reliable, changing the rate of recharge of the ground water, and increasing evaporation losses. Many rural communities are already experiencing reduced spring discharge and increased seasonal water scarcity, which is increasing reliance on tanker delivery and community water storage (Immerzeel et al., 2020; IPCC, 2021). Further demographic expansion is possible outside a more integrated urban water planning, hence this may exceed the water supply provided by freshwater resources in the area.

Groundwater Recharge and Spring Sustainability

Groundwater quietly provides important flow to the springs and is the source of water for domestic consumption, but glaciers predominate in the visible hydrology. Both snowmelt and glacier melt contribute to aquifer recharge in high-altitude catchments and reduced snow accumulation and accelerated runoff is likely to result in reduced aquifer recharge and spring discharge in these systems (Taylor et al., 2013; Bolch et al., 2019).

Climate variability and land-use change have been associated with decreases in discharge of springs in other parts of the Himalaya. Although there are limited systematic studies of the hydrogeological conditions in Ladakh to date, the trends observed suggest an increasing vulnerability for the spring-fed communities with future climate change (Immerzeel et al., 2020; IPCC, 2021). Improved groundwater monitoring and management of springsheds should be viewed as priorities for adaptation, rather than something added on.

Water Quality and Ecosystem Health

Water quality is as influenced by climate driven hydrological change as is water quantity. River turbidity and chemistry is altered by increased sediment, dissolved minerals and naturally occurring contaminants mobilised from more glacier melt. Meanwhile, decline in streamflow leads to lower dilution capacity of streams, thereby increasing the concentration of pollutants originating from settlements, tourism and farming (Milner et al., 2017; Bolch et al., 2019).

The change of flow regimes also has ecological consequences such as afforestation of alpine wetlands and loss of riparian vegetation and cold-water aquatic ecosystems associated with year-round glacier-fed streams. Habitats may be less suitable for aquatic organisms during the summer with lower discharges and warmer waters, leading to decreased biodiversity and ecosystem services like nutrient cycling and carbon sequestration (IPCC, 2021; Milner et al., 2017).

Water-Related Hazards and Disaster Risk

The challenge of climate change also increases the risk of water-related hazards in glacierized mountain areas. As glaciers retreat more rapidly, there is an increased likelihood of the formation of unstable moraine-dammed lakes, resulting in the potential for a catastrophic downstream damage event called a Glacial Lake Outburst Flood (GLOF) (Allen et al., 2019; Shugar et al., 2021). Warming temperatures and thawing permafrost create additional slope instability that is contributing to debris flows and sediment transport overwhelming roads, bridges, irrigation canals and hydropower infrastructure (Gruber & Haeberli, 2009; Bolch et al., 2019).

As a warmer atmosphere carries more moisture (Thayyen et al., 2013; IPCC, 2021), extreme precipitation events (such as the 2010 Leh cloudburst) are likely to increase, leading to a two-fold challenge for Ladakh: increased quantity amid extreme precipitation and decreased availability in other circumstances.

Socio-economic Implications for Water Security

The impact of water insecurity extends beyond production to people's livelihoods, public health, tourism and the regional economy. Unreliable irrigation reduces farm revenues and increases the risk faced by farmers' households. The water scarcity has a detrimental impact on the tourism infrastructure which now forms a big part of the economy of Ladakh. This competition, driven by the demand of domestic tourism, agriculture, industry and nature is likely to increase if water governance does not respond (Nüsser et al., 2019; Schmidt & Nüsser, 2017).

To face this challenge in the long-term, integrated water resources management (IWRM), climate-resilient infrastructure, efficient irrigation, groundwater conservation, glacier monitoring and governance featured by the actual participation of local communities, scientists, and policymakers will be key (UN-Water, 2021; Immerzeel et al., 2020).

Adaptation Strategies and Sustainable Water Resource Management

The retreat of glaciers and growing water insecurity demands a shift of focus from traditional water management towards integrated climate-resilient adaptation. The indigenous knowledge and scientific innovation in Ladakh already intertwines to deal with the seasonal scarcity and dwindling glacier snows, while at the same time allowing for increased uncertainty in hydrological forms. Local initiatives have proven effective in a few selected cases but, future water security will require cohesive efforts in the area of technology, watershed management and policy, and in long-term observations of the cryosphere (Nüsser et al., 2019; Bolch et al., 2019; IPCC, 2021).

Traditional Ecological Knowledge (TEK) and Indigenous Water Management

The traditional ecological knowledge of the Ladakhis has helped them to survive the harsh climate for centuries. While fighting over water in scarcity is nothing new, there have long been mechanisms for equitably distributing glacier meltwater to all users—indigenous irrigation systems (yuras), community water management, water rotation and customary governance institutions (Nüsser et al., 2012; Dame & Nüsser, 2011). The regulatory model of village water managers, called churpons, is a genuine governance system for a scarce resource, regulating the timing for watering, setting up the conflict resolution and coordinating the maintenance of the canal (Schmidt & Nüsser, 2017).

This resilience is enhanced by traditional farming which practices efficient water use, mixes crops, implements organic farming and grows crops resistant to drought (such as barley and buckwheat). However, these institutions are being pushed by rapid social and economic change: labour shortages, tourism expansion, and livelihood change (Nüsser et al. 2019, Dame & Nüsser 2011) and it will be essential to couple indigenous knowledge with water management in the modern era.

Artificial Glaciers and Ice Stupas

Adaptation techniques that are more creative in Ladakh involve the artificial replenishment of water as ice, through the snow placed in Ice Stupas and the artificial glaciers constructed by storing melted snow in an underground chamber attached to the glacier to free up the stored water when it is the time to flow, in the spring or summer. The artificial glacier idea was introduced by Chewang Norphel, which uses dams created in the shaded part of the stream channel that cause the water to physiologically freeze during the winter to form a natural seasonal glacier store (Norphel & Tashi, 2014). I founded on that concept by Sonam Wangchuk, an architect who constructed the Ice Stupa, a conical structure out of ice which melts slowly during early growing season, providing some irrigation water before the natural glacier melt. (Wangchuk, 2014).

Use of Pilot projects has shown the potential for increased water availability early in the season and increased establishment probability of crops and reduced stress on irrigation leading to better yields in water stressed villages (Nüsser et al., 2019; Schmidt & Nüsser, 2017). How effective they ultimately are, however, relies on the local topography, availability of water, temperature variation during the winter months, as well as attentive maintenance and community acceptance – and the utility of the hydrological and economic benefits of scaling them up more generally needs to be better evaluated.

Integrated Watershed and Springshed Management

Integrated Watershed Management (IWM) and springshed management have been proven efforts to enhance water security in mountain areas in general. Watershed management is aimed at promoting land use sustainability, afforestation, slope stabilisation, contour trenching, check dams, recharge structures and soil and water conservation measures; all of which helps to improve recharging of groundwater and reduce the surface run-off (Sharma et al. 2016; IPCC 2021).

Springshed management takes it one step further, specifically looking at springshed recharge areas, to restore the degraded land and enhance infiltration that will maintain sustainable water flow to springs. It has seen some significant use in other Himalayan states such as Sikkim and Uttarakhand and there is reason to believe that similar measures can be implemented in Ladakh as well, where many villages e.g. Yarkand and Galden overcome even more severe water shortages using spring-fed water today (Negi & Joshi, 2002; Taylor et al., 2013). Enhanced long-term groundwater resilience here could benefit from a mix of hydrogeological mapping, water level monitoring and community engagement.

Climate-Smart Agriculture and Water Use Efficiency

To support food security in the face of climate change, it is vital to manage the use of agricultural water more efficiently. Climate smart agriculture (CSA) refers to water efficient technologies, improved varieties that are resistant to drought, crop diversification, improved soil moisture conservation and precision water management, which seek to sustain crop productivity and minimize water use (FAO, 2013; IPCC, 2022).

The scarcity of water leads to significant loss in open irrigation systems and in that setting drip and sprinkler irrigation systems have proved real potential in Ladakh. The high invertibility, which is common in southern horn of Africa countries, and in addition the mulching, use of conservation agriculture and greenhouse or protected cultivation, result in even less evapotranspiration and prolong the already short growing season (Nüsser et al., 2019; Schmidt & Nüsser, 2017). These, coupled with considering climate-responsiveneness for irrigation scheduling, may help to meaningfully enhance water productivity and water-use efficiency as water security is increasingly challenged.

Remote Sensing, GIS, and Climate Monitoring

With its incorporation of remote sensing, GIS and geospatial modelling, glaciers and water resources are now monitored in a much different way in these high altitude areas. The area of glaciers has been measured by satellite missions since the 1970s when Landsat first became available, encompassing Landsat, Sentinel, MODIS, ASTER, ICESat-2, and the Gravity Recovery and Climate Experiment (GRACE), as has been snow cover, glacial lakes, evapotranspiration, and land-use change (Bolch et al., 2019; Gardner et al., 2013).

Integrating these satellite observations with hydrological models (like SWAT, HBV and glacier mass balance models) improves projections of future water availability (Huss & Hock, 2018, Immerzeel et al., 2020). A combination of remote sensing and field observations, weather stations, streamflow monitoring and community-based data collection would provide a boost to evidence-based water management and early warning for hazards related to glaciers for Ladakh.

Policy Frameworks and Integrated Water Governance

Water security requires long-term planning and governance which integrates climate adaption, cryospheric conservation and disaster risk reduction, with sustainable development. The NAPCC and the National Mission for Sustaining the Himalayan Ecosystem (NMSHE) have both identified water resources as being vulnerable in the Himalayas and have highlighted the need for monitoring its glaciers, preservation of its ecosystems and adaptation (Government of India, 2010). The National Water Policy, on the other hand, advocates stakeholder Engagement in the water sector, provisions for Integrated Water Resources Management (IWRM), and for Demand-side Management and also groundwater conservation.

In reality, however, poor institutional understanding and coordination of responsibility, low-density hydro-meteorological data and limited glacier monitoring and weak involvement of research and local governance slow glacier monitoring efforts in Ladakh (Bolch et al., 2019; IPCC, 2022). That lack of coordination between institutions, limited climate services, inadequate investment in hydrological infrastructure and lack of community involvement in decisions could be mitigated.

Future Directions for Climate-Resilient Water Management

Going forward, they suggest to extrapolate into a joint framework developed from a combination of innovative scientific approaches and local knowledge, tying the fields of cryosphere, hydrology, and society together. Some priorities are to install the long term glacier observatories, increase the hydro meteorological monitoring, to support groundwater assessment, to introduce nature-based solutions, to encourage water efficient agriculture and to enhance climate forecast (Immerzeel et al., 2020; Azam et al., 2021). New technologies including AI, machine learning, water monitoring through IoT, aerial monitoring by drones, and climate digital twin hydrological models provide novel opportunities to manage water and climate risks in real-time in high elevation areas (IPCC 2022; Bolch et al. 2019).

It will ultimately depend on making sure that sustainable water security in Ladakh can be captured in a single, cohesive and climate-resilient development agenda that incorporates elements of integrating traditional knowledge, restoring ecosystems, technologising, adaptive governance and interdisciplinary research.

Research Gaps and Future Perspectives

The global warming of the Himalayas and how it influences the dynamics of glaciers and hydrology is complex and needs to be better understood, though significant strides are being made in knowledge of the subject; knowledge gaps exist on the specific case of Ladakh and the cryosphere–water security nexus in particular. Previous studies have focussed on glacier mapping, climate change trends, or hydrology to date, and few have followed an interdisciplinary approach to include aspects of glacial hydrology, ecology, socio-economics, and governance. Closing these gaps is important in the context of supporting evidence-based adaptation in an area of the world that is one of the most climate-sensitive mountain regions (Bolch et al., 2019; Immerzeel et al., 2020; IPCC, 2022).

Limited Long-Term Monitoring of Cryospheric Processes

Maybe the greatest deficiency is that there are relatively few long-term field observations, of glacier mass balance, of snow accumulation, of glacier thickness, of permafrost, and of streamflow. Continuous instation measurement exists only on a few glaciers and most glacier assessment in Ladakh is based on the use of satellite data (Bolch et al., 2019; Azam et al., 2021). Despite this, remote sensing is useful but cannot fully replace field work to validate and support theses observations when it comes to glacier thickness change, internal ice dynamics, snow density and subglacial hydrology (Gardner et al., 2013; Zemp et al., 2019). There is a need for permanent glacier observatories, weather stations, snow monitoring sites and discharge gauges in representative catchments, which should be a national priority.

Inadequate Understanding of Groundwater and Springs

Traditionally, water security studies in Ladakh have focused on glacier-fed rivers while less study has focused on groundwater systems. Glacier melt/snow melt, ground water recharge, spring discharge and aquifer storage are between them poorly understood, even though they are increasingly important for the supply of domestic water in the region (Taylor et al., 2013; Bolch et al., 2019). Groundwater modelling, springshed assessments, isotope hydrology and hydrogeological mapping are essential to determine the recharge mechanisms and to identify adopting sustainable groundwater strategies, as the climate continues to change (Negi & Joshi, 2002; Immerzeel et al., 2020).

Uncertainty in Climate and Hydrological Projections

While some certainty exists that the Himalaya will continue to warm, there is considerable uncertainty regarding future precipitation, western disturbance frequency and intensity, snowfall patterns and seasonal runoff patterns (IPCC, 2021 and Dimri et al., 2015). However, many models that are currently used to simulate glacier hydrology are simplistic, and the snowmelt and groundwater interactions are often poorly captured, leading to a limited reliability of the model predictions (Huss & Hock, 2018; Kraaijenbrink et al., 2017). Future studies should combine high-resolution regional climate models, glacier mass balance models, distributed hydrologic models, and formal uncertainty analysis for more creditable projections for local water resource planning.

Limited Evaluation of Adaptation Strategies

Strenuous efforts have been made locally to adapt to climate change, such as artificial glaciers and Ice Stupas, as well as the adoption of climate-smart farming and community-based irrigation, and some initial success has been found (Nüsser et al., 2019; Schmidt & Nüsser, 2017). Comparative evaluations across climatic zones, catchments and socio-economic contexts are needed to determine which are the most effective interventions in terms of resilience across the varying outcome of future climate conditions, ideally informed by integrated indicators; water availability, agricultural productivity, ecosystem health, cost-effectiveness and community acceptance.

Need for Advanced Technologies and Digital Water Management

The development of Earth Observation technology and digital technologies has provided unprecedented opportunities that allows the monitoring of the Himalayan Cryosphere. High-resolution satellite images, the use of drones, LiDAR, InSAR and ICESat-2 now enable detailed monitoring of glacier change in elevation, snow cover and glacier lake dynamics (Gardner et al., 2013; Bolch et al., 2019). The inclusion of artificial intelligence and machine learning, IoT sensors and digital twin hydrological models could further advance the monitoring of glaciers, prediction of streamflow, drought predictions, and water allocations (IPCC, 2022). Moving forward, these technologies will need to be combined with field observations and traditional knowledge to create truly climate-aware and real-time water management.

Strengthening Policy Integration and Community Participation

Demand for and delivery of water security cannot be without demand for water and action on water governance. Currently the water management in the Ladakh region is divided among the various institutions working for gemstones, irrigation, ground water, tourism, disaster and rural development, which results in disjointed decision-making and lack of coordination (Government of India, 2010; UN-Water, 2021). Future policies to consider should include true IWRM principles that combine the theme of climate adaptation, watershed restoration, groundwater conservation, and disaster risk reduction. Local water governance — supported by water users' participation, traditional institutions and citizen science — might be effective in achieving more meaningful improvements to water policy implementation and adaptation outcomes (Nüsser et al., 2019; IPCC, 2022).

Future Perspectives

Ecosystem-based management, traditional ecological knowledge and scientific innovations are thus crucial for water security in future in Ladakh. The real resilience requires interdisciplinary research that combines disciplines of climate science, glacier dynamics, hydrology, groundwater, ecology, and socio-economics under the same context for analysis. Monitoring of glacier mass balance should be a near-term research priority, as well as the establishment of hydro-meteorological observatories at high altitudes, advancing the understanding of groundwater, increasing transdisciplinary cooperation and combining remote sensing with process-based modelling (Bolch et al., 2019; Azam et al., 2021; Immerzeel et al., 2020).

On the policy side, it is important to focus on sustainable watershed management, efficient irrigation, recharging groundwater reservoirs, glacier hazard monitoring, ecosystem recovery and building climate-resilient infrastructure. Adaptive water governance in high altitude settings may be considerably improved by increasing investments in AI-based hydrological forecasting, IoT-based water monitoring, and participatory decision-support tools. In the end, safeguarding Ladakh's water resources in the context of climate change will require a comprehensive strategy that integrates scientific research, technological advancements, governance measures and community engagement to foster environmental sustainability and well-being for future generations

Conclusion

One of the most important environmental issues of the cold arid ecosystems of Ladakh is climate change. Glaciers in this region have been in retreat due to the effects of rising temperature, reduction in snowfall, changes in precipitation pattern and increase in climatic variability which has accelerated the glacier retreat and changed the cryospheric processes which are controlling the hydrology of this region. Glaciers and seasonal snow pack are the major freshwater storage in the region of Ladakh, which implys very severe impacts on water availability, agriculture productivity, ecosystem integrity, disaster risk, and socio-economic development (Bolch et al., 2019; IPCC (2021); Immerzeel et al. 2020).

The evidence collated here reveals that, despite the spatial variations (which are related to topography, debris cover, elevation and local climate), the overall glacier response in Ladakh is of glacier thinning, negative glacier mass balance, decreasing glacier snow persistence and increase of hydrological uncertainty (Azam et al., 2021; Gardelle et al., 2012; Bolch et al., 2019).

Initially, the accelerated melting causes an impact of increased river discharge (known as the peak water phenomenon); following glacier recession, melt water contribution is expected to decrease, resulting in a loss in irrigation water, drinking water, ground water recharge and ecological sustainability (Huss & Hock, 2018; Kraaijenbrink et al., 2017; Immerzeel et al., 2020).

Beyond hydrology, there are impacts from the cryospheric degradation. The livelihood of most rural communities still relies on agriculture, and its becoming much more difficult because of seasonal water shortages and changing timing of the meltwater for irrigation (Nüsser et al., 2019; Schmidt & Nüsser, 2017). Meanwhile, urbanisation, tourism, infrastructure development and population growth are placing strain on the limited freshwater resources. Water-related hazards like flash floods, GLOFs, debris flows, and slope instability are also increasing in frequency and severity due to climate change, and pose a threat to critical infrastructure and communities (Allen et al., 2019; Shugar et al., 2021; IPCC, 2022).

Despite this, there is some adaptive capacity to tap into in Ladakh. Unique examples of locally implemented adaptations are to be found in community-managed irrigation, traditional ecological knowledge, artificial glaciers, the preservation of the Ice Stupas, watershed restoration and climate-smart agriculture. However, these must be accompanied by continued technological developments, such as glacier monitoring, hydrogeology, remote sensing, and GIS, as well as hydrological modelling and early warning systems, to guarantee their effectiveness in the long term (Bolch et al., 2019; Gardner et al., 2013; Huss & Hock, 2018).

This review also highlights key research gaps, including inadequate glacier mass balance measurements over long time scales, a lack of understanding of groundwater – cryosphere interaction processes, uncertainty in climate projections, a lack of evaluation of adaptation strategies and gaps in governance. The interdisciplinary research on these will need to be complemented by long-term cryosphere observatories, mathematics and statistics-based cryosphere monitoring, hydro-meteorological monitoring, improvement of glacier and hydrological models, stronger monitoring by and with local communities to provide the solid evidence that the climate adaptation community demands (Azam et al., 2021; Taylor et al., 2013; Zemp et al., 2019).

Going forward, the water security of Ladakh will be determined by implementing integrated, ecosystem-based, climate-smart water management. The policy makers should focus on implementing Integrated Water Resources Management (IWRM), conserving ground water, restoring watershed and springshed, assessing glacier hazard, efficient use of irrigation water, and providing sustainable tourism practices while expanding institutional responsibilities and participation of communities (UN-Water, 2021; IPCC, 2022). The potential for using emerging technologies—AI, machine learning, water monitoring platforms based on IoT, high resolution Earth observation data and digital hydrological modelling—for better climate forecasts, water allocation and preparedness for disasters in glacier dependent mountain regions is very real (Bolch et al., 2019; Immerzeel et al., 2020).

Ultimately, cryosphere protection equals water security in Ladakh, as the cryosphere can be considered a true key component of environmental sustainability and social resilience. Inaction is not an option and proactive adaptation is needed as glacier dynamics and hydrological processes will continue to change as a result of climate change this century. Equitable and sustainable access to freshwater, conservation of sensitive mountain ecosystems and capacity to cope with the future changing climate will require an integrated approach – combining scientific studies, technological innovations, traditional ecological knowledge, participatory governance and evidence-based policy, to enable Bhutan to plan for the Himalayas.

References

1. Allen, S. K., Zhang, G., Wang, W., Yao, T., & Bolch, T. (2019). Potentially dangerous glacial lakes across the Tibetan Plateau. Nature Communications, 10, 4877. https://doi.org/10.1038/s41467-019-12847-9
2. Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Ramanathan, A., Favier, V., Mandal, A., & Pottakkal, J. G. (2021). Review of the status and mass changes of Himalayan–Karakoram glaciers. Journal of Glaciology, 67(261), 181–202. https://doi.org/10.1017/jog.2020.99
3. Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066), 303–309. https://doi.org/10.1038/nature04141
4. Bhambri, R., Bolch, T., Chaujar, R. K., & Kulshreshtha, S. C. (2013). Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. Journal of Glaciology, 57(203), 543–556. https://doi.org/10.3189/002214311796905604
5. Bolch, T., Shea, J. M., Liu, S., Azam, M. F., Gao, Y., Gruber, S., et al. (2019). Status and change of the cryosphere in the Extended Hindu Kush Himalaya region. In The Hindu Kush Himalaya Assessment (pp. 209–255). Springer. https://doi.org/10.1007/978-3-319-92288-1_7
6. Bond, T. C., Doherty, S. J., Fahey, D. W., et al. (2013). Bounding the role of black carbon in the climate system. Journal of Geophysical Research: Atmospheres, 118(11), 5380–5552. https://doi.org/10.1002/jgrd.50171
7. Dame, J., & Nüsser, M. (2011). Food security in high mountain regions: Agricultural production and water use in Ladakh, India. Food Security, 3(2), 179–194. https://doi.org/10.1007/s12571-011-0128-7
8. Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T., & Sikka, D. R. (2015). Western disturbances: A review. Reviews of Geophysics, 53(2), 225–246. https://doi.org/10.1002/2014RG000460
9. FAO. (2013). Climate-smart agriculture sourcebook. Food and Agriculture Organization of the United Nations.
10. Gardelle, J., Berthier, E., & Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. Nature Geoscience, 5, 322–325. https://doi.org/10.1038/ngeo1450
11. Government of India. (2010). National Mission for Sustaining the Himalayan Ecosystem (NMSHE). Department of Science and Technology.
12. Gruber, S., & Haeberli, W. (2009). Mountain permafrost. Nature Geoscience, 2(9), 628–629. https://doi.org/10.1038/ngeo616
13. Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change, 8(2), 135–140. https://doi.org/10.1038/s41558-017-0049-x
14. Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2020). Importance and vulnerability of the world's water towers. Nature, 577(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y
15. IPCC. (2021). Climate Change 2021: The Physical Science Basis. Cambridge University Press. https://doi.org/10.1017/9781009157896
16. IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press. https://doi.org/10.1017/9781009325844
17. Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017).

Impact of a global temperature rise of 1.5°C on Asia's glaciers. Nature, 549(7671), 257–260. https://doi.org/10.1038/nature23878

18. Milner, A. M., Khamis, K., Battin, T. J., et al. (2017). Glacier shrinkage driving global changes in downstream systems. Proceedings of the National Academy of Sciences, 114(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114
19. Müller, J., Dame, J., & Nüsser, M. (2020). Urban Mountain Waterscapes: The Transformation of Hydro-Social Relations in the Trans-Himalayan Town Leh, Ladakh, India. Water, 12(6), 1698. https://doi.org/10.3390/w12061698
20. Negi, G. C. S., & Joshi, V. (2002). Drinking water issues and development of spring sanctuaries in the Indian Himalaya. Mountain Research and Development, 22(1), 29–31.
21. Norphel, C., & Tashi, P. (2014). Snow water harvesting in the cold desert in Ladakh: An introduction to artificial glacier. In H. K. Nibanupudi & R. Shaw (Eds.), Mountain Hazards and Disaster Risk Reduction (pp. 199–210). Springer Japan
22. Nüsser, M., Dame, J., & Kraus, B. (2019). Irrigation and development in the Upper Indus Basin: Characteristics and recent changes of a socio-hydrological system in central Ladakh, India. Mountain Research and Development, 39(2). https://doi.org/10.1659/MRD-JOURNAL-D-18-00072.1
23. Nüsser, M., Schmidt, S., & Dame, J. (2012). Irrigation and development in the upper Indus Basin: Socio-hydrological interactions in Ladakh. Die Erde, 143(4), 307–330.
24. Palazzi, E., Filippi, L., & von Hardenberg, J. (2019). Insights into elevation-dependent warming in the Himalayas. Climate Dynamics, 52, 3755–3777. https://doi.org/10.1007/s00382-018-4360-z
25. Pepin, N., Bradley, R. S., Diaz, H. F., et al. (2015). Elevation-dependent warming in mountain regions of the world. Nature Climate Change, 5(5), 424–430. https://doi.org/10.1038/nclimate2563
26. Ramanathan, V., & Carmichael, G. (2008). Global and regional climate changes due to black carbon. Nature Geoscience, 1(4), 221–227. https://doi.org/10.1038/ngeo156
27. Scherler, D., Bookhagen, B., & Strecker, M. R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience, 4(3), 156–159. https://doi.org/10.1038/ngeo1068
28. Schmidt, S., & Nüsser, M. (2017). Changes of high-altitude irrigation in Ladakh under climate and socio-economic transformation. Mountain Research and Development, 37(3), 312–323. https://doi.org/10.1659/MRD-JOURNAL-D-16-00077.1
29. Sharma, E., Molden, D., Rahman, A., et al. (2016). The Hindu Kush Himalayan Monitoring and Assessment Programme. ICIMOD.
30. Shea, J. M., Immerzeel, W. W., Wagnon, P., Vincent, C., & Bajracharya, S. (2015). Modelling glacier change in the Everest region. The Cryosphere, 9, 1105–1128. https://doi.org/10.5194/tc-9-1105-2015
31. Shugar, D. H., Jacquemart, M., Shean, D., et al. (2021). A massive rock and ice avalanche caused the 2021 Chamoli disaster. Science, 373(6552), 300–306. https://doi.org/10.1126/science.abh4455
32. Taylor, R. G., Scanlon, B., Döll, P., et al. (2013). Ground water and climate change. Nature Climate Change, 3(4), 322–329. https://doi.org/10.1038/nclimate1744
33. Thayyen, R. J., Dimri, A. P., Kumar, P., & Agnihotri, G. (2013). Study of cloudburst and flash floods around Leh, India, during August 2010. Natural Hazards, 65(3), 2175–2204. https://doi.org/10.1007/s11069-012-0464-2

34. UN-Water. (2021). Summary Progress Update 2021: SDG 6—Water and Sanitation for All.
35. Wangchuk, S. (2014). Ice Stupa: Artificial Glaciers of Ladakh [Project description]. Indiegogo. https://www.indiegogo.com/projects/ice-stupa-artificial-glaciers-of-ladakh
36. Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., & Wang, L. (2022). The imbalance of the Asian water tower. Nature Reviews Earth & Environment, 3, 618–632. https://doi.org/10.1038/s43017-022-00299-4
37. Zemp, M., Huss, M., Thibert, E., et al. (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature, 568(7752), 382–386. https://doi.org/10.1038/s41586-019-1071-0
38. Gardner, A. S., Moholdt, G., Cogley, J. G., et al. (2013). A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science, 340(6134), 852–857. https://doi.org/10.1126/science.1234532