



The Global Social and Economic Consequences of Mountain Cryospheric Change

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The mountain cryosphere provides fresh water and other ecosystem services to half of humanity. The loss of the mountain cryosphere due to global warming is already evident in many parts of the world and has direct implications to people living in mountain areas and indirect implications to those who live downstream of glaciated river basins. Despite the growing concerns, the relationship between cryosphere change and human society has yet to be assessed systematically. A better understanding of how cryosphere change affects human systems and human security would provide much needed support to the planning of global and regional actions to mitigate impacts and facilitate adaptation. This paper synthesizes the current evidence for and potential impacts of cryosphere change on water, energy, food, and the environment in different mountain regions in the world. The analysis reveals that the changes in the cryosphere and the associated environmental change have already impacted people living in high mountain areas and are likely to introduce new challenges for water, energy, and food security and to exacerbate ecosystem and environmental degradation in the future. The effects of cryospheric changes are also likely to extend to downstream river basins where glacier melt contributes significantly to dry season river flows and supports irrigation, fisheries, and navigation, as well as water supply to many big cities. Appropriate adaptive and mitigative measures are needed to prevent risks and uncertainties from being further compounded.

Keywords: cryospheric change, water security, food security, energy security, climate change, environmental degradation, adaption measures, SDGs

INTRODUCTION

Mountains provide multiple ecosystem services vital for human well-being (Millennium Ecosystem Assessment, 2005; Messerli et al., 2007). Many of these services are related to the cryosphere—glaciers, ice sheets, snow cover, river and lake ice, permafrost, and seasonally frozen ground (Huggel et al., 2015). Mountains are often referred to as “water towers for humanity (Messerli et al., 2007) as the mountain cryosphere can store vast amounts of the Earth’s freshwater (Viviroli et al., 2011; DellaSala, 2013). The cryosphere regulates the climatic conditions of the Earth system, while seasonal melting of mountain snow and ice supplies freshwater for more than half of the world’s population (Qin and Ding, 2010; Xiao et al., 2015; Milner et al., 2017).

Globally, glaciers, permafrost, and other ice masses in mountain areas are thinning or declining in response to global warming and the associated changes in air temperature and precipitation

(IPCC, 2014; Zongxing et al., 2016; Milner et al., 2017, see also **Table S1**). Deglaciation rates in the high mountains have accelerated in recent decades, with both the area and volume of glaciers declining, with only a few exceptions (Bolch et al., 2012; Rabatel et al., 2013). An estimate of global glacier change indicated a mass loss rate of $259 \pm 28 \text{ Gt yr}^{-1}$ between 2003 and 2009, with global runoff from glaciers exceeding $1,350 \text{ km}^3 \text{ yr}^{-1}$ (Bliss et al., 2014). In the Andes, Bolivian glaciers have lost nearly 50% of their mass over the last 50 years (Rangecroft et al., 2013). The glacier on Mount Kilimanjaro in Tanzania has lost 85% of its area over the last 100 years, and it is unlikely that any ice will remain on it by 2060 (Cullen et al., 2013). Glaciers in the Alps have lost between 30 and 40% of their surface area and about half of their volume since 1900 (Paul et al., 2007; Beniston et al., 2018). Similarly, glaciers in the Tien Shan mountains in China have lost 6–18% of their area between 1961 and 2012 (Farinotti et al., 2015), especially in the Northern regions where loss of area ranges from 0.36 to 0.76% annually (Sorg et al., 2014).

The Hindu Kush-Himalayan (HKH) region is known as the “Third Pole” as it stores more snow and ice than anywhere else in the world outside the polar regions. But here too glaciers have been retreating very fast (Xu et al., 2009; Bolch et al., 2012; Laghari, 2013; Moors and Stoffel, 2013; Bahuguna et al., 2014). Glaciers in the Ganges, Indus, and Brahmaputra river basins are reported to be losing $24 \pm 2 \text{ Gt}$ of ice per year, equivalent to around 10% of the global loss of glacier mass between 2003 and 2009 (Gardner et al., 2013). In a recent comprehensive assessment, Bolch et al. (2019) concluded with high confidence that the trend of glacier changes—thinning, retreating, and losing mass—in the Himalayan region is expected to continue. Kranaijenbrink et al. (2017) projected that an increase of global temperature by 1.5°C would warm the high mountains of Asia by $2.1 \pm 0.1^\circ\text{C}$, which would lead to the disappearance of $49 \pm 7\%$ to $64 \pm 5\%$ of glaciers by the end of the century. Even if the Paris Agreement’s goal of limiting global warming to 1.5°C is realized, one-third of the Himalayan ice-volume is expected to disappear. Böhner and Lehmkuhl (2005) predicted that by 2100, glaciated regions in the Himalayas will decrease by 43–81% under the annual mean temperature increases described in the IPCC SRES scenarios.

Scientists predict that about 50% of the glaciers in high mountain Asia, 80% of glaciers in the low latitudes of the South American Andes (**Table S2**) and European Alps, and 30% of glaciers in Alaska may disappear by the end of the 21st century (Huss et al., 2017).

Glaciers have a profound influence on streamflow, river runoff and water quantity and quality, and changes on it will have a wide range of impacts (Lafreniere and Sharp, 2005; Stahl and Moore, 2006; Bliss et al., 2014). Receding glaciers and less snowfall are expected to have implications on hydrologic patterns of our water systems with significance for mountain and downstream populations.

Natural and human systems are closely interconnected; changes in the physical systems of the cryosphere is expected to have an impact on both natural ecosystems and dependent human systems with impacts on socio-economic conditions, livelihoods, infrastructure, and living conditions (Kaltenborn et al., 2010; Carey et al., 2017; Mark et al., 2017). It is clear

that mountain populations will directly feel the impact of such changes when water sources change for irrigation and drinking, and there are increased threats of flooding or drought. However, the effects of cryospheric change extend significantly beyond the mountain regions (Milner et al., 2017). The cryosphere is a major source of water for hydropower, surface and groundwater irrigation for agriculture, livestock production, forestry, fisheries, and drinking water supplies (Hovelsrud and Smit, 2010; Huggel et al., 2015; Vincent et al., 2019).

Accelerated melting of mountain glaciers is likely to increase surface water flow in the short term but lead to a gradual decrease in the volume of water in glacier-fed rivers and streams in the longer term (Shrestha, 2005; Kaltenborn et al., 2010; IPCC, 2014; Sorg et al., 2014; Vuille et al., 2018). There are likely to be marked changes in the seasonal availability of water, with reduced storage of winter precipitation in the form of snow, and resultant reduction in water flow in the dry season (Fountain et al., 2012), without the buffering capacity of glacier melt. In combination with other factors, water shortages may affect agriculture and crop production and increase food insecurity.

The accelerated glacier melting is expected to increase the formation of glacial lakes and may exacerbate various water-induced natural hazards such as Glacial Lake Outburst Floods (GLOFs), increasing the susceptibility of infrastructure and loss of lives and property (Kaltenborn et al., 2010; Khanal et al., 2015). Thawing of permafrost may also release methane gas which can significantly contribute to atmospheric warming, while melting of snow, ice, and soil increases erodibility, leading to subsidence and infrastructure failure (Fountain et al., 2012). Changes in the cryosphere could impact tourism, energy generation, industrial production, socio-cultural structures, and human security, and hinder economic growth and exacerbate human risk (Biemans et al., 2013; IPCC, 2014; Carey et al., 2017). The impacts are expected to affect both mountain communities and those further downstream (Bury et al., 2011; Brown et al., 2015; Milner et al., 2017) and are expected to cause chain reactions in the social, cultural, economic, and environmental sectors at multiple spatial and temporal scales.

Over the last few decades, with growing concern about climate change and its impacts there has been a concerted effort to understand more about cryosphere change. While serious concern is consistently raised about the melting of ice reserves, in fact little attention has been paid to the human impacts. The possible social and economic consequences have yet to be systematically documented (IPCC, 2014; Carey et al., 2017). Better understanding of how cryosphere change affects human systems and human security is important for global and regional actions to mitigate impacts and facilitate adaptation.

Although the 4th and 5th IPCC assessment reports highlight the importance of “increasing emphasis on human beings, their role in managing resources and natural systems, and the societal impacts of climate change” (IPCC, 2014), the reports up to now provide only limited information on the relationship between cryosphere change and human society. This paper fills this gap by synthesizing the impacts of cryosphere change on human systems, particularly on water, food, energy, and the environment, both in high mountain areas and downstream.

UNDERSTANDING THE LINKAGES BETWEEN CRYOSPHERE CHANGE AND HUMAN IMPACT

The cryosphere is an integral component of the Earth's natural system which interlinks and interacts with biological and human systems (Qin and Ding, 2010; Xiao et al., 2015). Different components of the cryosphere (e.g., glaciers, snow cover, and permafrost) are interconnected and play an integrated role in the climate system and local ecosystems (Derksen et al., 2012). Thus, changes in the mountain cryosphere can have significant consequences on terrestrial ecosystems, hydrology, and human systems (Bales et al., 2006; Derksen et al., 2012; Cramer et al., 2014). Understanding the impacts of cryosphere change on human society, therefore, requires examining the complex linkages between the natural environment and humans, their processes, direct and indirect feedback, and effects at multiple scales (Warner, 2010; Derksen et al., 2012; Huggel et al., 2015). Changes in the cryosphere or in its size and/or certain characteristics of its components can affect the local and regional physical environment as well as the ecosystems and services people receive from them (Warner, 2010; Fountain et al., 2012; Berman and Schmidt, 2019). These changes can affect human society directly through changes in hydrology, streamflow, ground water recharge, air temperature, disasters, living conditions, infrastructure and transportation, and indirectly through the effects on changing ecosystems and their services (Millennium Ecosystem Assessment, 2005; Fountain et al., 2012).

The effects of cryosphere changes are non-linear, interactive and highly complex, and often cascade from one stress to another, one sector to another, and one place to another (Galaz et al., 2011; Cramer et al., 2014; Lawrence et al., 2018). For instance, the melting of glaciers and the resultant glacial lake outburst floods (GLOFs) can trigger various other events. Such events may aggravate land degradation, increase variations in the hydrological regime and degrade biodiversity, which in turn can increase socioeconomic vulnerabilities (McDowell et al., 2013; Carey et al., 2017). Manifestations of vulnerabilities in one sector or place can cause vulnerabilities in other places. For instance, changes in the hydrological regime, especially in the dry season, may affect agriculture, which may cause livelihood stress and compel poor farmers to migrate elsewhere, causing further social stress (Barnett and Adger, 2007; IPCC, 2014). The impacts are often indirect, invisible or distant, and their full extent is not immediately clear (Alcamo and Olesen, 2012; Lawrence et al., 2018). Some impacts are sudden and immediate, while others, such as the changing structure and function of ecosystems and the resultant loss of ecosystem services available to humans (Grimm et al., 2013), may emerge gradually over several years and decades (Alcamo and Olesen, 2012). Impacts can also be seasonal with strong inter-annual variability (Dirmeyer and Brubaker, 2007). However, humans too can have profound impacts on the cryosphere in various ways. Water quantity and quality, for instance, can be impacted (de Jong et al., 2009) when humans adopt unsustainable adaptation practices, such as artificial snowmaking and constructing ski

runs equipped with pipelines and reservoirs to promote winter tourism (de Jong, 2011, 2015).

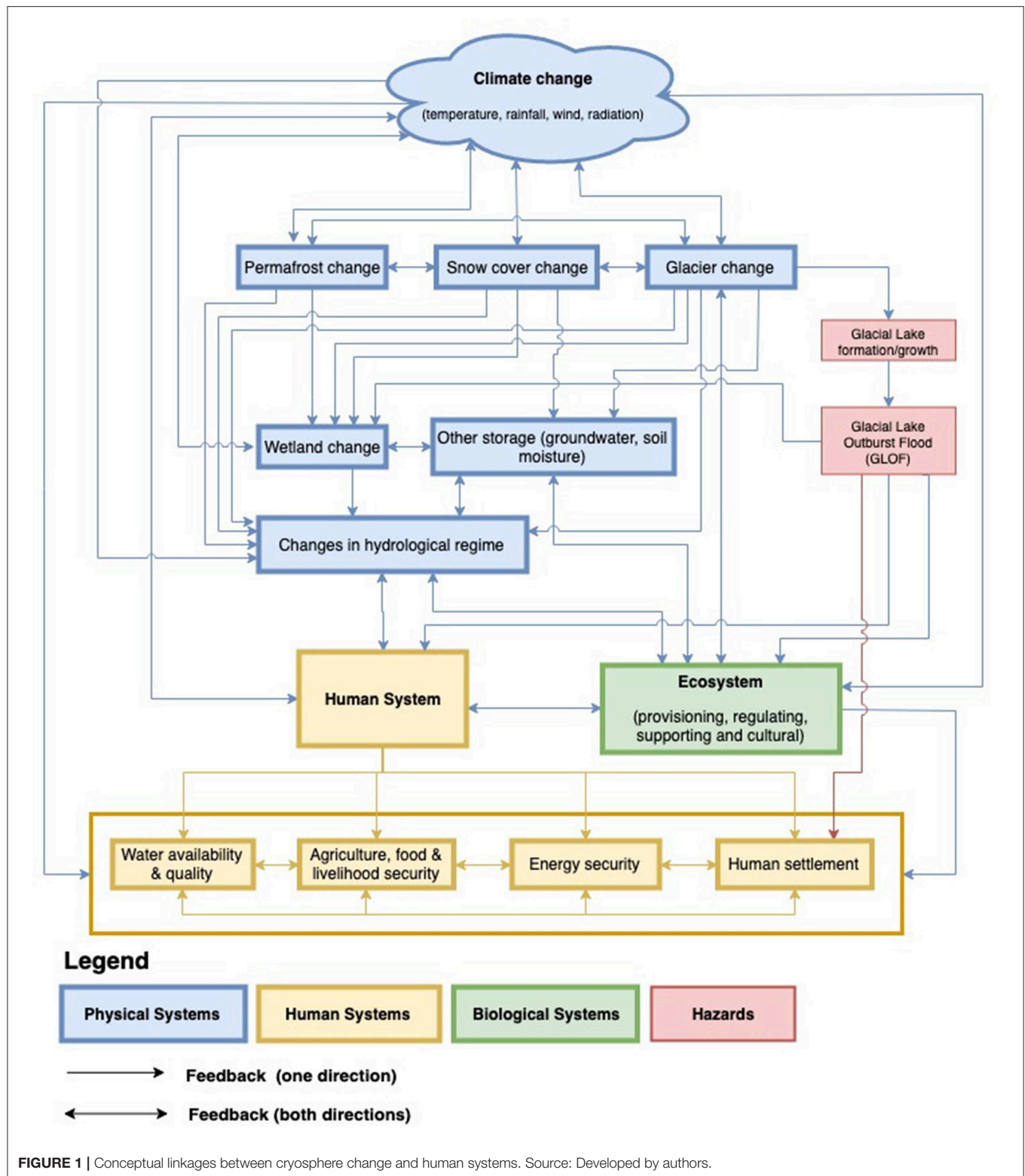
The effects of cryosphere change extend well beyond their origins. Initially, accelerated glacier melt may increase a glacier's contribution to river flow as a result of its negative mass balance (Lutz et al., 2016), but the effect is temporary and will decline with decreasing glacier size (Pouyaud et al., 2005). Rapid cryosphere changes are likely to impact local water availability and quality, and exacerbate disasters which in turn may affect water, livelihood, food, and energy security at a regional scale (Biemans et al., 2013; IPCC, 2014). **Figure 1** summarizes the conceptual linkages between physical cryosphere change, the ecosystem, and human systems in a schematic form.

METHODS

To synthesize the information, we adopted a systematic review approach. The literature search was guided by two broad questions: (1) What are the observed impacts of cryosphere change on water, food, energy security, and the ecosystem in high mountain areas? And (2) what are the expected impacts of cryosphere change on water, energy, food security, and the environment in the downstream glaciated river basins? Our primary focus areas were the Andes, Alps, Tien Shan, and Himalaya mountain ranges, however we also used examples from other mountain regions, such as the Rocky Mountains.

We collected information from diverse sources, but our primary focus was on peer-reviewed journal articles. As many journal articles do not touch upon social and economic aspects of cryosphere change, we also included book chapters, research reports, government documents, and conference papers. The keywords used in search string terms included combinations of "cryosphere change," "social impacts," "economic impacts," "glacier melting," "snowfall," "permafrost," "streamflow," "river runoff," "water availability," "irrigation water," "agriculture," "hydropower," "tourism," "livestock," "fisheries," "livelihood," "human security," "disasters," "GLOF," "ecosystem," and "environment." We selected documents based on the following criteria: (1) the documents recorded or referred to the observed and projected impacts of cryosphere change; (2) the documents cover any of the mountain ranges of Andes, Alps, Tien Shan, Himalaya, and other high mountain regions; (3) the documents were published in the English language. The main **exclusion criteria** were (1) the documents referred to impacts that were not, fully or partly, related or attributed to the changes of any components of cryosphere; (2) documents were not written in the English language.

We began the search with Scopus but expanded to Google Scholar and ResearchGate to fill in the gaps. While searching, we also looked at titles, abstracts, and keywords to avoid irrelevant documents in addition to the inclusion exclusion criteria stated above. We found 390 unduplicated documents over a period of 25 years (1994–2019) relevant to our research questions. These 390 documents were studied thoroughly, keeping the inclusion



criteria, research questions and relevance in mind. Unsuitable documents were thereafter dropped. This resulted in 185 non-duplicated papers that were suitable to use in this study. We used

these documents to identify social and economic implications of cryosphere change for people living in mountain areas and the downstream river basins, particularly on water, energy, food

security, and the environment. The next section presents the result of the analysis.

RESULTS: HYDROLOGICAL, SOCIO-ECONOMIC, AND ECOLOGICAL IMPACTS

Cryospheric Change Shifting Hydrological Regimes

Much of the human impacts of cryospheric change will be reflected in water systems as people are highly dependent on river flow and groundwater for cities, irrigation, and energy, much of which has its source in mountain areas. There is already mounting pressure in many areas of the world due to limited water resources, and too little or too much water, available at different times will stretch water management capabilities. Moreover, there is another pressing challenge to keep enough water in the environment to maintain a range of aquatic ecosystem services including fisheries and to provide enough outflow into oceans to keep saltwater intrusion at bay (Forslund et al., 2009).

Each river system in each mountain will have a different response to cryospheric change due to different hydrological systems. However, as ice and snow turn into a liquid state due to global warming, the contribution to streamflow from the cryosphere will increase up to a point in time when ice reserves shrink to such a size that release of water slows down, and the contribution starts to diminish (Huss and Hock, 2018; Vuille et al., 2018). This turnover point, or “peak water” will happen in different mountain regions at different times. Many glaciers have already reached their peak contribution to stream flow in the Andes (Baraer et al., 2015; Huss et al., 2017; Vuille et al., 2018) and most regions of British Columbia (Stahl and Moore, 2006). In the Hindu Kush Himalayan region, most glaciers are yet to reach their peak runoff, and for many this is expected to occur at the middle of this century (Bolch et al., 2019), snowfall pattern is changing (Viste and Sorteberg, 2015).

Typically, annual river hydrographs show a pattern of peak discharge coinciding with high rainfall or snow or glacier melt. There are also low flow periods, and societies have learned to store water, for example with reservoirs, to level out any imbalance so that water is available throughout the year. Nevertheless, water shortages could increase vulnerability through increased dependence on reservoirs during water shortages (Di Baldassarre et al., 2018). Societies have also adopted their practices to grow irrigated crops when water is available. The cryosphere has an important role to play in storing water, often releasing it during the dry season. Losing this natural water storage will require further adaption by people to cope with climate change.

Ten large socio-economically and culturally important rivers have their origin in the Hindu Kush Himalaya. The rivers flowing within South Asia are dominated by monsoon patterns, swelling during the summer monsoon rainy season but drying up during the remaining 6 to 8 months. These heavily populated regions depend heavily on this water, and people have adapted to these

wet and dry cycles. With not much reservoir storage, people have turned to groundwater to meet their needs, a situation that is not sustainable over large parts of South Asia. The cryosphere releases water during the dry months, providing a precious resource when it is most needed. In addition to cryosphere change, the region will also face a change in rainfall patterns, with the annual volume of rain expected to increase in the future but with more intense rainfall events surrounded by drought periods. The buffering effect of the cryosphere reserves is expected to be lost.

Alterations of the hydrological regimes brought about by cryospheric and climate changes may affect society and the economy by reducing water availability across different sectors (Barnett et al., 2005; Berman and Schmidt, 2019) as well as by intensifying water-induced natural hazards including floods, droughts, avalanches, and landslides (Haeberli and Whiteman, 2015; Stäubli et al., 2018; Allen et al., 2019). Due to floods, avalanches and landslides, along with other climatic stresses, mountain regions have incurred significant economic losses over the last 30 years (from 1985 to 2014). It is estimated that such losses amount to up to US\$ 45 billion in the Hindu-Kush Himalaya region, US\$ 7 billion in the European Alps, and US\$ 3 billion in the Andes (Stäubli et al., 2018). Economic loss and damages due to cryospheric-induced disasters are also reported in other mountain regions and are projected to further increase. The Zhangzangbo GLOF in Tibet, China, in 1981 killed 200 people and incurred an estimated economic loss of US\$ 456 million. It caused severe damage to the Nepal–China Highway, which incurred a cost of US \$3 million to rebuild (Mool et al., 2001). Similarly, the Dig Tsho GLOF in the Khumbu Himal of Nepal in 1985 damaged a hydropower plant and other properties and its estimated economic loss was US\$ 500 million (Shrestha et al., 2010).

Cryospheric-induced disasters are projected to increase in the future and will require additional costs in risk reduction measures and maintenance, as well as protection of infrastructure, going as far as relocation of communities to safer places. For instance, the adaptation cost of digging a canal into the Tsho Rolpa glacier in Nepal to lower the glacial lake costed US\$ 3 million in 2002 (Bajracharya, 2010). Cryosphere-induced disasters have also increased livelihood stress and physical risk and affected human settlement. Due to several GLOFs and disruption of irrigation canals, the entire villages of Passu and the communities of Northern Borith and Ghulkin in northern Pakistan were forced to migrate to higher ground (Parveen et al., 2015).

Moreover, the degradation of permafrost and consequent land and soil instabilities may bring additional challenges to the existing infrastructure, including roads, dams, and buildings. For instance, roads in the Northwest Territories of Canada have become unreliable with the operating seasons being considerably shortened owing to thawing of permafrost. This has affected food transport to the northern communities as well as domestic and international trade (Warren and Lemmen, 2014). The Diavik diamond mine, for instance, incurred an additional expense of \$11.25 million to fly 15 million liters of fuel when the operational season of the road was reduced from 70 to 42 days (Warren and Lemmen, 2014).

In addition to the damages caused by natural disasters, shifting hydrological regimes may cause additional risk and challenges, affecting the society and economy in multiple ways. The following sections describe the key challenges besides observed and potential impacts of cryospheric changes.

Cryospheric Change Brings Challenges to Water Security

Accelerated glacier melting and changes in the cryosphere pose a risk to future water security, as about two billion people currently live in water-stressed areas (UNESCO World Water Assessment Programme, 2019). In high mountain areas, people depend to a great extent on snow, ice, and glacier meltwater to be used for drinking water, domestic use, agriculture, livestock, and other economic activities. In several regions, including the Hindu Kush Himalayas and tropical Andes, water scarcity is likely to increase regardless of the climate change scenario and speed and magnitude of glacier retreat, owing to population growth, urbanization and industrialization (Buytaert and De Bièvre, 2012; Buytaert et al., 2017). Cryosphere shrinkages, however, will compound the problem. Glaciers, an important source of water, have been retreating in highland Peru since 1962, in turn reducing dry season stream flow. As a result, local communities are experiencing water shortages in the dry season (Bury et al., 2011) (Table S2). In the Himalayan region as well, many areas are already experiencing water shortages (Tiwari and Joshi, 2015) which are projected to increase in the future. The Indus and Ganges basins in particular are likely to face increased risks and uncertainties in water availability (Immerzeel et al., 2010; Bolch et al., 2012). In the Tien Shan region of China, a 20% reduction of glacier volume was observed for 446 glaciers between 1964 and 2004, which is already impacting the sustainability of the region's water sources (Wang et al., 2014). Table 1 presents some of the evidence for impacts that have already been observed.

Although these individual pieces of evidence available are small and not representative, collectively they clearly indicate that cryospheric change has already impacted water availability for irrigation, agriculture, and livestock in some parts of the Himalayas and Andes as well as water quality in some parts of the Alps, Himalayas, and Western United States. These impacts are expected to intensify in the future due to projected changes of the cryosphere.

Cryospheric Change May Affect Downstream Water Availability

While mountain communities are the most affected, downstream communities will also be affected by cryosphere change as they rely to a considerable extent on mountain areas for water, and a reduction in glacial coverage after peak water is expected to lead to low flows and drought conditions in the long run (Van Tiel et al., 2018). For instance, more than 800 million people live in the catchments of the Indus, Ganges, and Brahmaputra rivers, with a vast majority living in the plains. They all rely to varying extents on the water released from glaciers for drinking, food production, and others, especially during the dry season (Immerzeel et al., 2010; Kaser et al., 2010; Lutz et al., 2014; Rasul, 2014). The Himalayan cryosphere contributes to as much as 70%

of the Indus River System, which flows on the plains (Tahir et al., 2015) and supports large irrigation systems. Changes in the cryosphere in high mountain areas are likely to have serious implications for these downstream populations (Barnett et al., 2005; Milner et al., 2017), especially during the dry season when water demand for agriculture and energy is high.

Cryospheric Change Compounds Urban Water Challenges

The water supply for many large cities and towns originates, at least in part, from the cryosphere (Vergara et al., 2007; Kinouchi et al., 2019). The Andes, for example, supply 15% of the total water to the large cities of La Paz and El Alto in Bolivia, 20% to the city of Huaraz, Peru, and 5% to Ecuador's capital city of Quito. The glaciers of Cordillera Real supply 30–40% of the potable water to La Paz and El Alto (Vergara et al., 2007). Seasonality is also significant, with glaciers contributing to critical low flow during less favorable periods. The three main dams that supply La Paz and El Alto no longer receive runoff from glaciers and have almost run dry. The two Tuni-Condoriri glaciers which provide part of the water for El Alto and La Paz lost 39% of their area between 1983 and 2006 (Buxton and Escobar, 2013). The Chacaltaya glacier, another source for these cities, is expected to completely disappear within 15 years (Buxton and Escobar, 2013). Recession of Andean glaciers will affect the water supplies to major cities, putting populations and food supplies at risk in Argentina, Bolivia, Chile, Colombia, Ecuador, Peru, and Venezuela (Vuille et al., 2018), clearly an area of major concern.

Even in the HKH region, many big cities in mountain and downstream areas depend partially on glacier and snowmelt water for municipality water supply. For example, the glacier-fed Melamchi River supplies 3.5 million liters of water per day to a population of 600,000 in the Melamchi Valley and is planned to supply 170 million liters per day to more than 1.5 million or more people in the capital city of Kathmandu (Khadka and Khanal, 2008). High-mountain villages are directly dependent on melt water for domestic water supply and irrigation, and some villages in the high mountain areas of northern Pakistan have relocated to other places as glacier supplies have diminished and irrigation systems have been disrupted (Parveen et al., 2015).

Lowland areas are some of the most densely populated areas in the world. Moving downstream from mountains, rainwater becomes a more important contributor to river flow. Nevertheless, large and growing cities will require as much water as possible throughout the year. In India, large cities such as Haridwar, Varanasi, Patna, Kanpur, Allahabad, Munger, Bhagalpur, Delhi, Agra, Mathura, and Kolkata are all located along the Ganges and its tributaries, with huge populations depending at least partly on glacier and snow melt that feed the rivers and recharge groundwater. The Simly Dam water reservoir for Islamabad in Pakistan is supplied by the Soan River, and water seepage from the glacier-fed Indus Basin Irrigation System is an important source of water for southern Punjab (Jehangir et al., 1998).

With growing populations becoming wealthier and urbanized, the demand for water will continue to rise, and providing adequate water to the growing population will be a challenging

TABLE 1 | Examples of observed impacts of cryospheric change on water availability and quality.

Mountain region	Observed impacts	Sources
Ladakh and Zaskar, Jammu and Kashmir, India, Himalaya	Increased glacier recession and decline in snowpack, combined with other climatic factors, leading to water shortage for irrigation	Clouse, 2016; Clouse et al., 2016; Nüsser et al., 2018
Gilgit Balistan, Pakistan, Himalaya	Thinning of glaciers and decline in snowmelt water, affecting water availability for irrigation	Parveen et al., 2015; Nüsser and Schmidt, 2017
Uttarakhand, India, Himalaya	Gradual decrease in snowfall causing drought and reducing reliability of water flow in arid and semi-arid areas	Chauhan, 2010
Khumbu, Nepal, Himalaya	Decrease in snowfall and increasing variability causing reduction in river discharge and reduced water availability for households and agriculture	McDowell et al., 2013
Tien Shan , China	A 20% reduction in glacier volume of 446 glaciers in the Ebinur lake basin between 1964 and 2004 impacting the sustainability of the region's water sources	Wang et al., 2014
Cordillera Blanca, Peru, Andes	Glacier retreat combined with other climatic factors leading to water scarcity affecting agriculture and livestock management	Bury et al., 2011; Chevallier et al., 2011
Bolivia, Andes	Shrinkage of two of the Tuni-Condoriri glaciers and the Chacaltaya glacier has reduced water supply from dams to major cities such as La Paz and El Alto	Buxton and Escobar, 2013
Germany, southeastern France, northern Italy, Central, and Eastern Europe, Alps	Receding glaciers and decline in snowfall reducing river discharge for population dependent on alpine water	Beniston et al., 2011; Beniston and Stoffel, 2014
Switzerland and northern Italy, Alps	Release of pollutants such as polychlorinated biphenyls (PCBs) and dichlorodiphenyl trichloroethane (DDT) into glacier-fed lakes	Schmid et al., 2011; Morselli et al., 2014
Ganges tributaries, Himalaya	Glacier melt contributing to the release of pollutant loads such as polychlorinated biphenyls (PCBs) and polyaromatic hydrocarbons (PAHs) during the dry season	Sharma et al., 2015
Western United States	Increased temperature and reduced snowpack have amplified hydrological droughts and shortages of water in California, the Colorado River Basin, and the Rio Grande	Gonzalez et al., 2018
Western North America	Decreasing amount of water in spring due to shrinkages of glaciers and changing snowpack	Stewart et al., 2005; Brown et al., 2019

task in the future. The contribution from the cryosphere varies depending on the situation, and in most instances very little is known about the direct contribution. However, this change in flow pattern due to vanishing cryospheric water will add complexity to an already water-stressed situation. It can cause conflicts between different water users (Gleick, 2014) as happened in Peru in 2008 when farmers and a hydroelectricity company disagreed on the operation of the Lake Paron Reservoir (French et al., 2015; Vuille et al., 2018).

Cryospheric Change May Affect Water Quality and Health

Glaciers can regulate the influence of harmful contaminants through storage in snowpacks, which prolongs the opportunities for volatilization and other transformations (Grannas et al., 2013), but as glaciers recede this effect will be reduced. Similarly, glacier retreat and longer-term decline in streamflow could reduce the capacity of streams to dilute pollutants such as industrial effluent and non-point source contaminants such as agrichemicals (Moore et al., 2009; Brown et al., 2015). In Peru, it is estimated that an additional cost of US\$ 100 million will be required to purify the deteriorating water quality resulting from cryospheric changes (Vergara et al., 2007).

Glacial meltwater could also potentially contribute to water pollution. Melting glaciers represent a secondary source of previously deposited and stored persistent organic pollutants (POPs), which are now being released back into the environment due to the accelerated melting induced by global warming (Donald et al., 1999; Blais et al., 2001; Bettinetti et al., 2008; Bizzotto et al., 2009; Bogdal et al., 2009). The release of historically deposited pollutants could significantly reduce water quality downstream (Milner et al., 2017). An unexpected increase in environmental pollution by POPs such as polychlorinated biphenyls (PCBs) and dichlorodiphenyl trichloroethane (DDT) was reported in a study of Lake Oberaar in Switzerland, which is directly fed by meltwater from the adjacent Oberaar Glacier (Bogdal et al., 2009), and an increase in levels of PCB was reported in Lake Stein in Switzerland, which is fed by the Stein Glacier. In Lake Iseo in northern Italy, the highest levels of DDT contamination were found during the period corresponding to the greatest glacier retreat (Bettinetti, 2011), and in a number of alpine lakes, POP concentration levels were related to the volume of meltwater (Morselli et al., 2014). Blais et al. (2001) found that 50–90% of POPs in glacier lakes originated from glacial meltwater. In the Himalayas, pollutant loads released by glaciers melting during the dry season can exceed the loads

from other sources in the catchment areas of river basins (Sharma et al., 2015).

Many communities living in the high mountains of developing countries depend on glaciers and streams for drinking water. Even in developed countries, indigenous people use glacier melt water for drinking. For instance, a majority of the indigenous population in Iqaluit, Canada, prefer collecting freshwater from natural sources such as streams, lakes, and icebergs. With the thawing of permafrost, they are now at risk of being exposed to contaminated water and water-borne pathogens (Warren and Lemmen, 2014). Deteriorating water quality resulting from changes in the cryosphere may directly affect human health, while the reduction in water supply and agricultural production resulting from glacier recession may also have health impacts (Singh et al., 2010).

Cryospheric Change as a Risk for Food Security

The high mountain areas in developing countries still have a considerable population dependent on agriculture, forestry, fisheries, pasture, and tourism for their livelihoods and food security, and depend on snow and glacier melt water for irrigation and subsistence agriculture for maintaining soil moisture and vegetation growth and groundwater recharge (Bury et al., 2013; Paudel and Andersen, 2013; Parveen et al., 2015; Clouse et al., 2016). High mountain agriculture and agro-pastoralism are particularly vulnerable to changes in the cryosphere as they depend on spring and summer runoff from melting snow and ice for irrigation (Dame and Nusser, 2011; Parveen et al., 2015; Clouse et al., 2016).

Some regions of the Himalayas, such as Afghanistan, northern Pakistan, and north western India, are completely dependent on snow and glacial meltwater for irrigation (Parveen et al., 2015; Clouse et al., 2016; Mukherji et al., 2019). In northern India, the gradual recession of low-lying glaciers over the last three decades has reduced the supply of irrigation meltwater available to farmers and caused chronic drought in many subsistence agricultural villages (Grossman, 2015). In Ladakh, India, agricultural production is entirely based on irrigation. Channels divert meltwater from glaciers and snowfields or, where topography allows, from the main rivers to settlements (Dame and Nusser, 2011; Vincent et al., 2019). In Gilgit-Baltistan in Pakistan, glacier and snowmelt water irrigates 66% of the total irrigated land, and in Melamchi Valley in Nepal this number is 100% (Khadka and Khanal, 2008; McDowell et al., 2013). Melting glaciers, thinning snow cover and changing precipitation patterns are affecting subsistence agriculture and the agro-pastoral system in many high mountain areas of the world (Table 2).

Besides high mountain areas, many irrigation systems in the plains rely on glacier- and snow-fed rivers (Mukherji et al., 2015; Schoolmeester et al., 2018). Glacial melt water is used for irrigation mainly in the Himalayas, the Andes, the Alps, and in the Central Asias Tien Shan and Pamir mountains (Punkari et al., 2014; Mukherji et al., 2015; Buytaert et al., 2017; Vincent et al., 2019). The Indus Basin Irrigation System, for instance, is fed by water from six glacier- and snow-fed tributaries; it irrigates 80%

of the total cultivated area of Pakistan (ICIMOD, 2010), which produces 85% of rice and wheat as well as all the sugar in the country, among others (Qureshi, 2011). Similarly, the Bhakra-Nangal irrigation system in Himachal Pradesh, India, supplies irrigation water to fields in Haryana, Punjab, and Rajasthan, producing a large amount of food. It has contributed significantly to making India self-sufficient in food grain and reducing hunger and food insecurity (Malik, 2008). In the Andes, surface glacial meltwater sustains farming in the Cordillera Blanca valleys and commercial agriculture in the lower watershed (Somers et al., 2016). In the Andes, glacial melt contributes to 45–100% of the irrigation water, irrigating 402,000 hectares of land in Bolivia, 79,300 hectares in Peru, 655 hectares in Chile, and 429 hectares in Argentina (Schoolmeester et al., 2018).

Over recent decades, reduced snow and loss of glacier mass has reduced water supplies in many subsistence agricultural villages across the Ecuadorian, Peruvian, and Bolivian Andes (Table 2). The canal water levels in the Yanamarey watershed of the Cordillera Blanca in Peru have been dropping over the past few years, especially during the dry season. It has become increasingly difficult to get sufficient water to maintain crop productivity (Bury et al., 2011). The frequency and intensity of low temperature frosts have also increased, which further damages crops. Households in the Cordillera Blanca in Peru reported that increasing climatic extremes and recession of the Andean glaciers have led to a decline in crop productivity, which poses a considerable risk to household food security (Mark et al., 2010; Vuille et al., 2018).

Livestock and Pastoralism

Animal husbandry is an important component of livelihoods and food security in high mountain areas, where animals are a source of food, skin, and wool and are also used for transport. Drying up of watering points due to cryosphere change could affect livestock production and food security. For example, in Wyoming in the USA, the cattle industry depends on glacial melt as a stable source of water during the growing season. However, the glacier surface area decreased on average by 32% between 1985 and 2005, and streamflow was reduced by 10% (Cheesbrough et al., 2009). Similarly, diminishing spring flows in the upper reaches of the Querococha watershed in the Cordillera Blanca in Peru, due to recession of the Andean glaciers, have negatively affected pasture health and grass productivity (Bury et al., 2011), while reduction in dry season water availability for livestock has also affected livestock productivity (Mark et al., 2010; Vuille et al., 2018). In the Nagqu Prefecture in Tibet Autonomous Region in China, the plant density in meadows has declined, in part due to cryosphere change, and this, together with increasing grazing intensity, has negatively affected yak and sheep herders (He and Richards, 2015) (Table 2). Overall, cryosphere change could have both positive and negative effects on agro pastoral livelihoods depending on the region, and more studies are needed to understand the possibilities.

Tourism

Tourism is an important source of income and livelihoods in mountain areas and supports a billion-dollar outdoor

TABLE 2 | Cryospheric change and its impacts on agriculture, livestock, fisheries, tourism, and food security.

	Region	Observed impacts	Sources
Agriculture	Urumqi, China	Early sprouting and maturity of seed in cereal crops; little increase in crop yield; and increasing drought events	Deng et al., 2011
	Jumla and Sindhupalchok, Nepal	Failure and uncertainty of rice and winter crops as a result of unpredictable rain/snowfall; diversification of crops and multicropping in response to changes in timing of snowfall	Sujakhu et al., 2016
	Uttarakhand, India	Crop loss due to irregular rain and snow patterns and reduced glacial melt affecting local food production with increased dependency on markets for food	Aggarwal, 2008
	Mustang and Manang, trans-Himalayan region, Nepal	Delay in start of vegetation growth season and decline in length of growing season as a result of snow decline	Paudel and Andersen, 2013
	Ladakh, India	Change in land-use practices and change in cropping pattern and food production because of decline in snowmelt	Dame and Nusser, 2011
	Cordillera Blanca, Peru	Decline in crop productivity caused by reduced water availability due to Andean glacier recession	Mark et al., 2010; Bury et al., 2011; Vuille et al., 2018
	Rhone river basin, Switzerland	Farmers forced to change to less water intensive crops in lowland areas of the Swiss Alps as a result of an increase in drought	Beniston, 2012
	Cordillera Blanca, Peru	Reduced growth rate, increase in diseases, and reduced livestock productivity caused by decline in glacier melt runoff during the dry season	Mark et al., 2010; Bury et al., 2011
Livestock	Tibetan Plateau, China	Less snowfall causing reduction of plant density affecting yak and sheep herders, together with increased grazing intensity causing reduction in soil organic carbon	He and Richards, 2015; Yuan and Hou, 2015
	Qinghai-Tibet Plateau, China	Reduction in soil moisture for alpine vegetation due to degradation of permafrost and resulting invasion by rodents	Huijun et al., 2009
Fishery	Kenai River, Alaska	Glacier melt and glacier outburst floods are affecting important fisheries and leading to a decline in the contribution of sport and commercial fishing to the economy	Milner et al., 2017
	Cordillera Blanca, Peru, Andes	Fish stocks are declining or disappearing in the upper watersheds due to glacier recession	Bury et al., 2011; Vuille et al., 2018
Tourism	Khumbu, Nepal, Himalaya	Reduced snowfall, and thus snowmelt, has reduced stream flow and affected water availability of water to meet the high demands of tourists	McDowell et al., 2013
	New Hampshire, New England, USA	Low-elevation ski areas have been abandoned because of a decline in snowfall	Hamilton et al., 2003; Steiger et al., 2017
	France and Germany, European Alps	Permafrost melting is affecting the stability of mountain huts, threatening tourist security, and income from tourism	Ravanel et al., 2013; Steiger et al., 2017
	Bhutan, Himalaya	Changes in snow cover have led to a shortening in the duration of the tourist seasons for trekking	Hoy et al., 2016
	Southwestern United States and Central Rocky Mountains	Decreases in winter snowpack and shortened snow seasons affected winter tourism and ski resorts	Burakowski and Magnusson, 2012

recreation service (Burakowski and Magnusson, 2012) but is being negatively affected by lower snowfall and receding glaciers (Table 2). In 2007, the Pastoruri Glacier in Huascarán National Park in Peru was closed to tourists because of its rapid recession, and tourist numbers have fallen from an estimated 100,000 in the 1990s to 34,000 in 2012 (Taj, 2013). Glacier ski resorts established in the 1970s and 1980s in Austria in the European Alps are now facing challenges related to the loss of glacier area thickness, decreased summer skiing season, and stagnation of tourist numbers (Falk, 2016). Similarly, the Chacaltaya ski resort in Bolivia, once declared the world's highest ski resort, closed recently due to glacier recession. This trend can also be witnessed in Ontario and Quebec in Canada, with a 10–15% decrease in ski tourism between 2000 and 2010 (Warren and Lemmen, 2014). In Switzerland, ski

areas are projected to decrease to 63% in a +2°C scenario and to 44% in a +4°C scenario, in reference to 85% in 1961–1990. Similarly, in Japan a 30% decline in skier visits is projected in a +3° scenario (Steiger et al., 2017). Similarly, the snowmobile industry is becoming increasingly vulnerable due to a lack of natural snow and skiing is becoming increasingly vulnerable due to dependency on snowmaking (Warren and Lemmen, 2014). Winter tourism in the United States is also at risk due climate-induced cryospheric change (Burakowski and Magnusson, 2012).

Fisheries

Many communities who depend on fishing as a source of livelihood could be affected by changes in glacier melt (Lehodey et al., 2006; Brander, 2007). For example, fish stocks in the

Yanamarey watershed in Peru have declined or completely disappeared due to seasonal reductions in fish habitat in the upper watershed resulting from glacier recession (Bury et al., 2011), which has affected the state economy. Increased glacier melting and glacier outburst floods in the Kenai river in Alaska have affected fisheries worth USD 70 million annually (Milner et al., 2017), while fish production in rivers from the Himalayan mountains has also become vulnerable (Allison et al., 2009), threatening income generation and dietary protein. Similarly, the warming of rivers and lakes has led to an expansion of invasive species in the Arctic and Continental Great Lakes ecoregions, which has increased commercial fishing but threatened the food security of the indigenous people, who for millennia depended on subsistence fishing (Warren and Lemmen, 2014).

Cryospheric Change as a Risk to Energy Security

Hydropower is an important source of energy, supplying about 16% of the world's electricity, and as much as 100% in Bhutan and Norway, 93% in Nepal, 59% in Canada, with up to 90% in Quebec, British Columbia, Manitoba, Newfoundland and Labrador, 33% in Pakistan (Shrestha et al., 2016) 80% in Peru, 50% in Ecuador, and a considerable amount in many Andean countries (Vergara et al., 2007). Water for these hydropower reservoirs and plants often originates from glacier and snow melt in high elevation areas, which is likely to be affected by climate change and accelerated glacier melting (Cruz et al., 2007; Boehlert et al., 2016; Turner et al., 2017). It is difficult to ascertain the exact impact of glacier recession on hydropower as the impacts can vary substantially across a region and even within countries, but different studies predict that it may eventually lead to marked impacts on the seasonality and volume of streamflow. The impact is likely to be greatest on small-scale "run of the river" hydropower plants (Kopytkovskiy et al., 2015) with little or no storage, which is a common type in the Himalayan region (Boehlert et al., 2016; Turner et al., 2017). While melting glaciers may increase water availability for hydropower at the initial stage, an increase in volume from meltwater does not necessarily lead to an increase in production of energy due to spillage effects from hydropower reservoirs (Warren and Lemmen, 2014; Tarroja et al., 2016). Reduction in dry season runoff can reduce hydropower production from these plants, as the initial increase in annual flow from glaciers will not compensate for decreased water availability during the dry season (Rees et al., 2004; Tarroja et al., 2016). For instance, severe drought in California in the United States resulting from higher temperatures and less snowfall has reduced hydroelectric generation by two-thirds from 2011 to 2015 (Gonzalez et al., 2018).

Climate change is also expected to increase the frequency and magnitude of extreme events, which is likely to increase the risk to hydropower plants from flash floods, debris flows, and similar events. Energy infrastructure such as transmission lines and powerhouses can be destroyed by GLOFs, which are also projected to increase. The Dig Tsho GLOF in Nepal in 1985 destroyed a hydropower plant worth USD 1.3 million, while a glacial fall near the Chorabari glacier, India, in June 2013 caused

an outburst that damaged hydropower projects in Uttarakhand (Schwanghart et al., 2016).

The energy sector is likely to suffer due to additional risk and loss of potential opportunities due to cryospheric changes. In Peru, the cost of glacier shrinkage for the energy sector was estimated to be about US\$ 740 million annually (Vergara et al., 2007), with a reduction of 11–15% in the production of electricity (Vincent et al., 2019). If glaciers from the Cordillera Blanca retreat, it would reduce meltwater runoff in the Cañón del Pato hydropower plant in Rio Santa by 50% and energy output would be reduced by about 300 GWh, and if the glaciers would disappear it would further decrease by about 600 GWh (Condom et al., 2012). Similarly, Switzerland, which generates over half of its energy from hydropower, is projected to lose about 21% of its annual inflow in the 2031–2050 period compared to 1991–2010, and further reduction in hydropower potential due to cryospheric shrinkages is expected (Gaudard et al., 2013). Additional investment will be required to repair, maintain, and adapt hydropower infrastructure due to cryosphere-induced disasters (Berman and Schmidt, 2019) and increased stress and demand for energy. For instance, Peru will be required to invest about US \$1 billion per gigawatt for thermal-based power to compensate for the loss of hydroelectricity (Vergara et al., 2007).

Cryospheric Change May Affect the Ecosystem and Environment

Ecosystems accustomed to long frozen periods are vulnerable to warmer temperatures. Cryosphere recession has serious implications for mountain ecosystems because of the effect on micro-climate, hydrology, vegetation, and the carbon balance (Fountain et al., 2012; Williams et al., 2015) and can also affect the ecosystems and environment downstream (Zhao-ping et al., 2010). Ice loss affects ecosystems directly through the loss of physical habitat and through alterations in thermal conditions, and indirectly by altering light and nutrient supply to primary producers (Fountain et al., 2012). Permafrost degradation can change soil moisture content and soil nutrient availability and influence species composition (Zhao-ping et al., 2010). The potential impacts include fragmentation of animal and plant communities and development of new assemblages, disruption of seasonally synchronized phenological connections among species, and losses in biodiversity with associated changes in ecosystem function (Parmesan, 2006), all of which can lead to environmental degradation. Permafrost recession can also affect slope stability and carbon balance, the release of trace gases, and hydrology (Slaymaker and Kelly, 2007).

Vegetation Patterns and Changing Ecosystem Productivity

Growth conditions for plants and the food chain for animals are directly affected by the thickness and duration of winter snow and its effect on soil water availability, energy input, and thermal conditions for biomass production. Winter snow cover is of great importance for soil processes (Edwards et al., 2007; DeBeer et al., 2016). Climate warming could reduce snowpack, which can lead to colder soils and an increase in the frequency of freeze-thaw cycles. Shorter duration of snow cover directly influences

the length of the growing season and the phenology of plant production and consumption (Gottfried et al., 2012; Warren and Lemmen, 2014). Permafrost degradation exacerbates surface erosion (Grannas et al., 2013; Warren and Lemmen, 2014). The disappearance of perennial ice and degradation of permafrost is likely to be accompanied by progressive drying of the surface and a decrease in vegetation cover. These factors will increase the effects of aeolian (wind) action and elevate the potential risk of desertification (Wang and French, 1994, 1995).

Upward Shifts of Species and Communities

Upward shifts of species and communities in response to a reduction in the cryosphere and warming climate are already evident in some mountain environments (Telwala et al., 2013). An analysis of worldwide tree line data indicated that the tree line had moved uphill in 52% of sites, and down in only 1% (Barros et al., 2017). In the Alps, upward movement of some plant taxa at a rate of 1–4 m per decade has been observed at higher elevations, together with a loss of some taxa that were formerly restricted to these elevations (Watson and Haeberli, 2004). Furthermore, concerning the riverine biodiversity, species of cold-adapted invertebrates from higher elevations are increasingly being displaced with the expansion of less cryophilic species due to a decrease in glacier runoff to streams, thus changing the hierarchical habitat template (Wilhelm et al., 2013).

Greenhouse Gases and the Carbon Pool

Large carbon pools have accumulated in the wetlands of the world's cold regions, primarily in peatlands. Much of this carbon is sequestered in permafrost (Jin et al., 1999; Schuur et al., 2008). Permafrost degradation is likely to increase the emission of major greenhouse gases from these layers, leading to further changes in the climate (Cheng and Wu, 2007). Nitrogen leaching from soils has also been reported to increase alongside a decrease in snowpack, which is potentially attributable to reduced root uptake and/or to physical (rather than microbial) degradation of soil organic matter (Freppaz et al., 2008). Recession of the cryosphere and resultant changes in vegetation could have a marked impact on the atmospheric exchange of greenhouse gases such as carbon dioxide and methane, which will impact ecosystem functioning (Callaghan et al., 2013). As mentioned above, there are considerable deposits of pollutants, especially POPs, stored in glacier ice. These are not only significant for water; melting of Arctic glaciers has released massive amounts of POPs back into the atmosphere, leading to a slight increase in the concentration of a variety of POPs in the Arctic atmosphere over the past 20 years (Ma et al., 2011), and a similar effect can be expected in other regions.

DISCUSSION

The evidence presented in “observed impacts” and “potential future impacts” has important implications on water management, food security, energy security, and environmental management. Existing trends and future projections suggest that the cryosphere is likely to shrink substantially in the coming decades at the current global warming rate. This is expected to change hydrological regimes in glacier-dependent

regions and affect river and stream flow, bringing additional risks and uncertainties to food, water, and energy security while exacerbating ecosystem and environmental degradation. Some of these effects are already being observed though their characteristics and magnitude of risks vary considerably across sectors and mountain regions (Table 3).

Although effects are difficult to quantify and existing studies are limited in scope, it is clear that cryosphere change will have a considerable impact on water availability in the future, both upstream and downstream. Evidence suggests that the impact will be more severe in arid and semi-arid mountain regions (Messerli et al., 2007), where peak water has already been reached and communities are already under water stress, and in high mountain areas in developing countries where people rely on cryosphere resources and ecosystems for their livelihoods heavily. Since glaciers are still melting with increased precipitation, the impacts are not clearly evident downstream, and the shortage of water availability is likely to emerge only gradually as glaciers increasingly vanish (Huss et al., 2017; Vuille et al., 2018). Furthermore, cryosphere change may bring additional risks to urban water supply, particularly in the Andes and the Himalayas, where the water supply of many big cities depends partly on water from glacier and snowmelt. As urbanization rapidly increases, cryosphere loss will pose management challenges for urban planners and managers in many mountain regions, particularly in the Andes and the Himalayas.

The agriculture sector is already experiencing adverse effects and is likely to be severely affected in the future. The effect of cryosphere shrinkage is likely to be felt beyond the mountain regions along the glaciated river basins. Changes in water availability due to cryospheric and climatic factors may immediately affect agricultural productivity in upstream areas and downstream areas in the long run. Glacier and snowmelt water contributes considerably to the supply of dry season irrigation water in the river basins of the Indus, Upper-Ganges, Upper-Brahmaputra, and Yangtze, which are the bread basket for billions of people in Asia (Siderius et al., 2013; Vincent et al., 2019). Similarly, the tourism sector, particularly winter sports in the Alps and North America, have already been affected negatively by snow reduction. In the future the industry is expected to become unviable, causing many to become jobless. Glacier shrinkage can also affect hydropower production in certain regions upon reaching peak water, impacting both energy security and mitigation of greenhouse gas emissions, thus posing challenges to reducing greenhouse gas emission and achieving the goals of the Paris Agreement (Gonzalez et al., 2018).

CONCLUSION AND RECOMMENDATIONS

Findings of this study indicate that the growing risks for water, food, and energy security, together with increasing risk of disasters, are expected to increase economic, social, and environmental vulnerabilities and to introduce new threats to human security (Matthew et al., 2009). The risks emerging from shrinkage of the cryosphere are adding challenges for sustainable development, particularly in achieving certain sustainable development goals (SDGs) such as ensuring water

TABLE 3 | Observed impacts and potential implications due to cryospheric change.

	Observed Impacts*	Potential future impacts	Future implications
Water Availability			
• Upstream water availability	Negative (Moderate–High)	Negative (High)	Implications to water security
• Downstream water availability	Negative/positive	Negative (High)	Water stress will increase after peak water, increased competing demand for water
• Urban water availability	Negative (Low–Medium)	Negative (High)	Threat to urban water supply
• Water quality and health	Negative (Low)	Negative (Moderate to High)	Health impacts
Food Security			
• High Mountain Areas	Negative (Medium to High)	Negative (High)	Can lead to chronic drought and threat to food security especially during dry seasons
• Downstream irrigated areas	Uncertain	Negative (High)	Large irrigation systems may suffer from water shortage and affect productivity
• Livestock and pastoralism	Negative (Low)	Negative (Medium)	Can lead to degradation of pasture health and reduced livestock productivity Threat to livelihood and food security
• Fisheries	Uncertain Depends on region and species	Uncertain Potential increase of commercial fishing Potential increase of invasive aquatic species	Threat to food security
Tourism (winter sports)	Negative (Medium–High)	Negative (High)	Threat to livelihood and economic security
Energy Security			
• Hydropower	Negative (Low)	Negative (Low–Medium)	Implications for energy sector and Green House Gas emission
Ecosystem			
• Vegetation patterns and ecosystem	Uncertain	Uncertain	Upward shift of invasive species in some regions and increased vegetation growth
• Greenhouse gases and the carbon pool	Negative (Low)	Negative	Increased emission of greenhouse gases from permafrost
Human Settlement and Infrastructure			
• Risk to Human Settlement	Negative (Low)	Negative (Medium–High)	Increased livelihood stress Increased outmigration Possible social conflicts
• Risk to Infrastructure	Uncertain	Negative (Low–Medium)	Additional costs and investment in maintaining and repairing and potential abandonment or relocation of infrastructure Affects food transportation

*Impact Categories: **Three categories:** Positive, Negative and Uncertain, **Positive:** three categories: Low, Medium, High, **Negative:** three categories: Low, Medium, High.

availability (SDG 6), achieving food security (SDG 2), ensuring access to affordable energy for all (SDG 7), and combating climate change (SDG 13).

Cryosphere loss is therefore likely to have far-reaching impacts on societies, the economy, the environment, and ecosystems if appropriate measures are not taken urgently. The adaptation measures taken so far are limited, fragmented, and narrowly focused (McDowell et al., 2019; Rasul et al., 2019). A comprehensive risk management plan at different levels will be needed to minimize the adverse impacts. Adaptation to climatic change vulnerability should be integrated into planning and management of socioeconomic development, and appropriate adaptive and mitigative measures to prevent risks and uncertainties from being further compounded urgently need to be addressed. Cryosphere change may otherwise undermine development efforts aimed at reducing poverty and achieving

food, water, and energy security by further triggering social conflicts and human insecurity.

Limitations and Further Research Needs

Quantification of the economic and social effects of cryosphere change is important in informing public policies and influencing adaptation decisions. This study, however, was not able to quantify the effects, owing to gaps in data, as most of the documents available are qualitative with limited scope and fail to develop a coherent approach. Further research is needed to quantify, assess, and predict the impacts of cryosphere change on the environment, society, and the economy and its effects on human security, outmigration, and social conflicts. Research is also needed to reduce uncertainties in projected changes in the cryosphere, their potential impacts and their long-term consequences on society, the economy, and the environment.

More interdisciplinary studies are required to better understand how the effects of cryosphere change cascade to the socio-economic sectors, increasing risks and human vulnerabilities, and what sustainable adaptation measures can be adopted on the long-run (de Jong, 2015).

Recommendations

While designing public policies and strategies to deal with the increasing uncertainty emerging from cryosphere shrinkage, a collaborative and integrated approach that considers the impact of water stress on agriculture, energy, food, and the ecosystem needs to be considered. The main points to consider are as follows:

- While cryospheric change affects water availability, managing the future water challenges will require both demand and supply management. Sustainable water storage will be critical for managing seasonal water variability, as cryosphere change is expected to affect the amount and seasonality of flow in most rivers. Reservoirs, however, should be managed carefully to avoid adverse effects on the environment and human settlement (Di Baldassarre et al., 2018). This is particularly important in regions like the HKH where seasonality in water availability is high and water storage is gaining importance.
- Efforts should be made to manage demand for water by improving water-use efficiency and reducing waste through appropriate policy incentives. As agriculture is the largest user of water, efforts need to be made to reduce water demand for irrigation by improving irrigation methods, changing cropping patterns and the crop calendar, and introducing other water-efficient methods.
- To deal with the possible impacts on hydropower generation and energy security, cryosphere change needs to be taken into consideration in designing hydropower plants. Efforts should be made to develop more efficient hydropower turbines and to reduce surface evaporation from reservoirs as well as to enhance energy efficiency and reduce wasteful consumption.
- Disaster response and preparedness need to be improved through better monitoring of risks and planning for risk management and by engaging multiple stakeholders. Governments have an important role to play in raising awareness about present and future impacts and vulnerabilities, building adequate capacity to cope with impacts, and in helping to put existing adaptation capacities into action. It is also necessary to improve research capacity to understand, assess, and predict impacts so that appropriate response measures can be developed.

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- Measures need to be taken to facilitate adaptation of high-mountain agriculture, fisheries, and livestock with the changes in snow and ice cover and their shifting patterns.
- The mitigation of cryosphere change mainly depends on actions to reduce greenhouse gas emissions, which will require substantial decarbonization of the global economy and energy system. Urgent global action is critical to reducing global warming. Addressing the impacts of cryosphere shrinkage will require regional and international cooperation to share experiences and knowledge as well as monitoring risks and facilitating adaption and mitigation measures.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript and/or the **Supplementary Files**.

AUTHOR CONTRIBUTIONS

GR: conceptualization, data collection, data analysis, writing, and revising. DM: conceptualization and writing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2019.00091/full#supplementary-material>

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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