INTERNATIONAL JOURNAL OF ENVIRONMENT
Volume-9, Issue-2, 2019/20 ISSN 2091-2854
Received: 28 March 2020 *Revised: 15 August 2020* *Accepted: 17 August 2020*

ADDRESSING CLIMATE CHANGE RISKS INFLUENCING CRYOSPHERE-FED KUHL IRRIGATION SYSTEM IN THE UPPER INDUS BASIN OF PAKISTAN

Arshad Ashraf[1]* and Ghani Akbar[2]
[1,2]Climate, Energy and Water Research Institute, National Agricultural Research Center (NARC), Chakshahzad, Islamabad, Pakistan
*Corresponding author: mashr22@yahoo.com

Abstract

Cryosphere-fed kuhl irrigation system forms a major lifeline for agriculture and livelihood development in the Himalayan region. The system is highly vulnerable to climate change impacts like glacier retreat, glacial lake outburst floods, snow avalanches and landslides especially in the upper Indus Basin (UIB). It is necessary to conduct reassessment of climate change impacts and find coping strategies for sustainable agriculture development in this mountainous region. In the present study, risks of glacier depletion , lakes outburst flood, snow avalanche and landslide hazards impacting cryosphere-fed kuhl irrigation system in 10 river basins of the UIB of Pakistan were analyzed using multi-hazard indexing approach. High risk of glacier depletion was observed in the Astore and Swat river basins likely because of the combined effect of reduced snow precipitation and rising warm temperatures in these basins. The risk of expansion in aggregate lake area was high in the Indus sub-basin, moderate in the five basins (i.e., Hunza, Shigar, Shyok, Shingo and Astore), while it was low in the four basins (i.e., Swat, Chitral, Gilgit and Jhelum). More than 2% areas of Hunza and Shigar basins in the Karakoram range exhibited high risk of snow avalanche and landslide (SAL) hazard, while moderate SAL hazard was found in >40% areas of Chitral, Gilgit, Hunza and Shigar river basins. An effective early warning mechanism and provision of adequate resources for preparedness are essential to cope with negative impacts of climate change on irrigated agriculture in this region in future.

Keywords: Cryosphere, Glacier depletion, Himalayan region, Hindu Kush, Karakoram

DOI: http://dx.doi.org/10.3126/ije.v9i2.32700

Introduction

The projected rise in temperature increases the likelihood of occurring of compound hazards to cause extreme impacts on natural and human systems (IPCC, 2019) including agriculture (Thapa et al., 2015; Shrestha, 2019) and socioeconomics (Bhattarai, 2015) in the Himalayan region and elsewhere (Stevanović et al., 2016; Al Jbawi, 2020). The severe effect of increased warming relates to increase in glacier melting and expansion of numerous glacial lakes observed in most of the Himalayas (Bolch et al., 2012; IPCC, 2014; Ashraf et al., 2017). The depletion of glaciers often causes interruption in melt-water flows to kuhl irrigation system, which ultimately impacts the agriculture as well as livelihood of the local communities (Ashraf and Batool, 2019). According to Savoskul and Smakhtin (2013), the glacier area indicated depletion at an annual rate of approximately 0.8–0.9%/year in the Indus basin during 1961-1990. The increase in snow and glacier melting usually exaggerates snow avalanche and glacial lake outburst flood (GLOF) hazards (IDRC, 2014). The lakes instability owing to rapid expansion is creating severe outburst flood hazard for the downstream communities (Costa and Schuster, 1988). The heavy discharge of water from Dig Tsho Lake in Nepal during 1985 resulted in damage of a hydropower plant and destruction of 14 bridges and other infrastructure in the downstream (ICIMOD, 2011). In another event, the outburst of Luggye Tsho lake in Bhutan during 1994 caused extensive damage to the residential buildings and infrastructure, besides loss of valuable lives along the Punakha-Wangdue valley (Watanabe and Rothacher, 1996; Richardson and Reynolds, 2000). The GLOF events occurred during 2003, 2007-2013, 2015 and 2017 had resulted in heavy damage to property and infrastructure besides loss of valuable lives in the upper Indus basin of Pakistan (DRM, 2013; Ashraf et al., 2014; Shaikh and Tunio, 2015; Wester et al., 2019; Ashraf and Rustam, 2020). The irrigation infrastructure was destroyed several times during those flood events, which ultimately affected the livelihood of local people. Similarly, landslide events resulting from seasonal climate impact, flooding, immature geology and human influence have highly affected this region (Rahman et al., 2011).

The intake water flow to the kuhl system is expected to decline with decrease in glacier size – the situation likely to be felt by communities of the Himalayan region depending mostly on snow and glacial melt water for their livelihood (Rao and Patil, 2017). Glacier retreat has ultimately contributed to localized decline in agricultural yields in the mountainous regime of Hindu Kush-Himalayas (IPCC, 2019). Within extensive Himalayan region, the Indus basin has the major human dependence on snow and ice melt (Kaser et al., 2010). The changes in climate are leading to increased vulnerability in the upper Indus basin, where water for irrigation comes from snow and glacier melt channelized via kuhl irrigation network (Nüsser and Schmidt, 2016; ICIMOD, 2017). Presently, more than 5000 kuhl irrigation schemes are active in irrigating about 70,000 ha of land in the Gilgit-Baltistan (PCRWR, 2009). In floods during 2015-16, the region was badly suffered owing to heavy avalanches and mudflows resulting in loss of 88 major irrigation channels in different localities of the Gilgit district (Hussain, 2018). In order to meet the future demand of food and fiber for growing population, there is an immense need to bring additional land under cultivation through effective irrigation management. Therefore, it is necessary to conduct reassessment of climate change impacts and find coping strategies for sustainable development of agriculture in this mountainous region.

The present study is focused on investigating risks of depletion of glaciers, lakes outburst flood, snow avalanche and landslide hazards impacting cryosphere-fed irrigation system in 10 river basins of the upper Indus Basin (UIB) of Pakistan. Multi-hazard indexing approach was adopted to assess the risk of these impacts using remote sensing data, local knowledge and ground information.

Geographical setup of the area

The study area consists of three major mountain ranges, i.e., Hindu Kush, Karakoram and Himalayas (HKH) comprising of 10 river basins in the upper Indus basin of Pakistan (Figure 1). The climate is dry continental, characterized by a great range in average temperatures and annual precipitation. Monsoon rainfall usually brings unprecedented splashes of intense and short duration storms which trigger flash floods and landslides during July-September period. According to the climate data of Pakistan Meteorological Department (PMD), and Water and Power Development Authority (1990–2012), annual rainfall in the northern valleys ranges within 125–500 mm received generally from the westerlies. Annual rainfall >500 mm occurs mainly in the southwestern parts comprising of Swat, lower Indus, Astore and Jhelum basins lying mostly in the monsoon-belt (Figure 2). Mean maximum temperature >20°C prevails in the southwestern parts, whereas <15°C is dominant in the northeastern parts of the study area. Similarly, mean minimum temperature >10°C is dominant in most of the southeastern parts and <5°C in the northeastern parts comprising of high altitude Karakoram and Hindu Kush ranges.

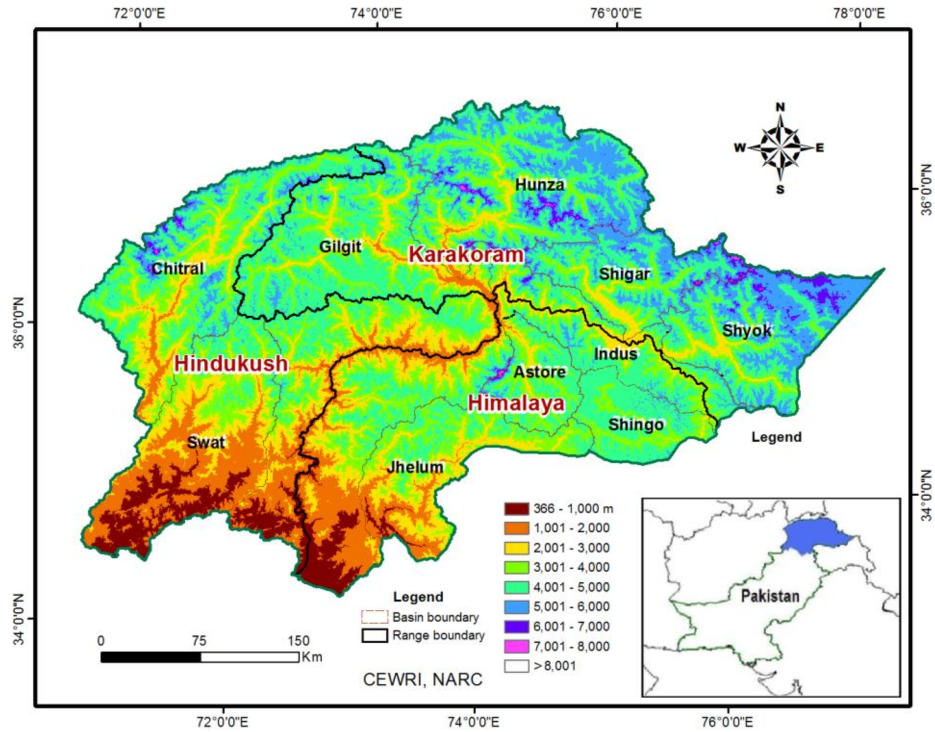

Figure 1. Location of different river basins and HKH ranges in the study area, northern Pakistan

The geology consists of various types of igneous and metamorphic rocks of Precambrian to Recent age (Hussain and Awan, 2009). In parts of lesser Himalayas and sub Himalayas in the southeast, alluvium deposits are common and geological structures are found mainly due to tectonic activities (Bossart et al., 1984). The glaciated region consists of numerous high mountain peaks, glaciers and lakes scattered at various places. Water for irrigation is derived primarily from snow *or* glacier melt diverted through farmer-constructed gravity-flow systems. The cryosphere-fed kuhl system is practiced over 65% of the irrigated area in the Gilgit-Baltistan (GoGB, 2013). In Chitral basin of the Hindu Kush, more than 1000 small communally-owned irrigation channels irrigate more than 20,000 ha. The main sources of livelihood in the region are subsistence agriculture and natural resources (IDRC, 2014).

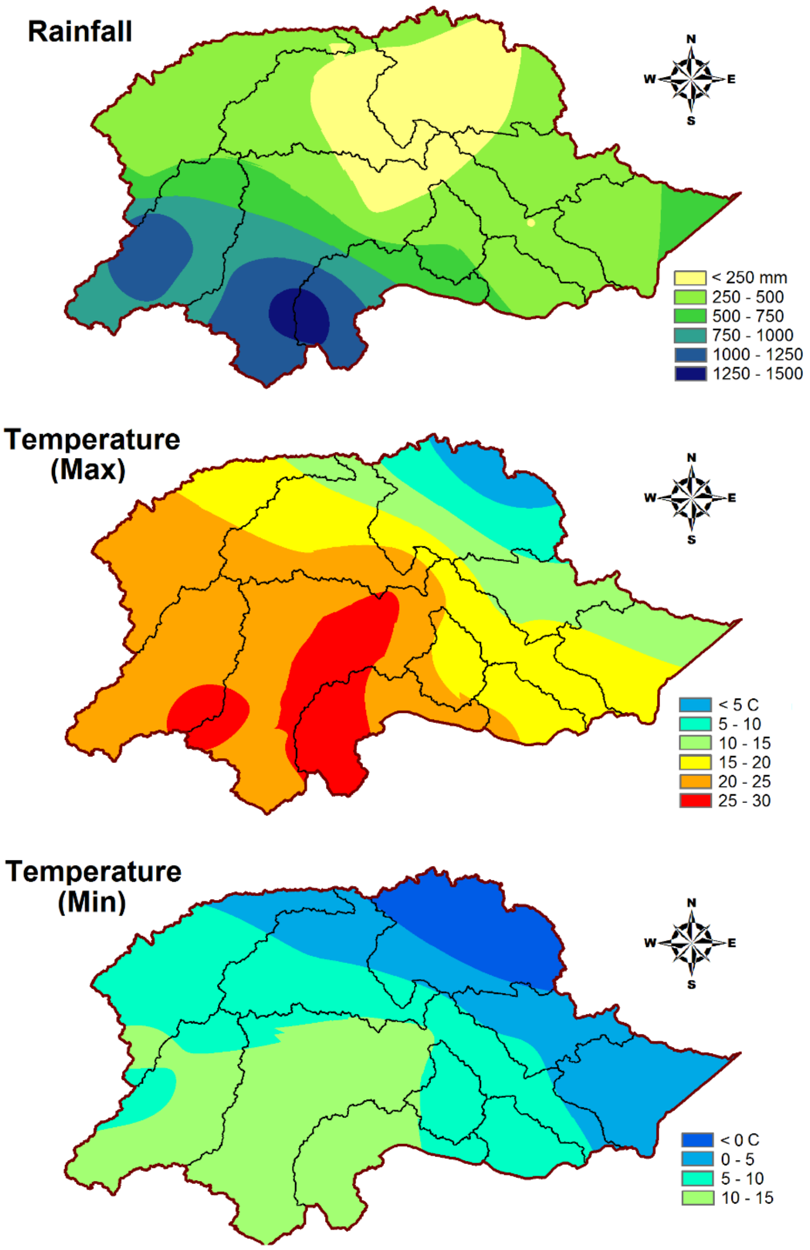

Figure 2. Mean Annual rainfall, maximum and minimum temperatures in various river basins of the UIB

Materials and methods

In this study we performed change analysis and classification of glacial resource based on aggregate ice reserve and lake area in different river basins using source data of glaciers and lakes of 2001 and 2013 inventories (Roohi et al., 2005; Ashraf et al., 2014; FTR, 2015; GIP, 2017). The previous studies were mostly based on temporal analysis of specific glaciers and lakes (e.g. Ives et al., 2010; Raj, 2010; Gardelle et al., 2011; Wang et al., 2015; Jain and Mir, 2019). We adopted multi-hazard indexing approach to assess the risk of depletion of glaciers, lakes outburst flood, snow avalanche and landslide hazards impacting cryosphere-fed irrigation system in 10 river basins of the UIB. The <5 km^2 size category of glacier was selected for establishing index of glacier depletion by volume (GDV) for risk analysis following Ashraf and Batool (2019). Overall, glaciers of <5 km^2 size category contribute 96.6% to the total glacier number in the study area and form an important source of melt-water for kuhl irrigation system. In the arid environment, local communities have to rely on ice melt of smaller glaciers residing over high mountains to sustain their livelihood (Figure 3). The information of glacial ice volume has importance for assessment of resource potential for establishing and sustaining cryosphere-fed kuhl irrigation system in this region (Ashraf and Iqbal, 2018; Ashraf and Batool, 2019).

High-risk level of GDV was assigned to >2.0 km^3 depletion in aggregate volume of glaciers in a basin, while moderate-risk level was assigned to <2.0 km^3 reduction in the glacial ice volume during 2001-2013 period. The low-risk level means no reduction in ice volume in a basin pointing towards safe condition for the irrigation system. In contrast, index of expansion in lake area (ELA) was developed under which high-risk level was assigned to >4.0 km^2 expansion in aggregate lake area of a basin and moderate-risk level to <4.0 km^2 expansion in the lake area during the 12-year period. The low-risk of ELA was considered for stable or shrinking lakes, i.e., exhibiting no expansion during 2001-2013 period. The ELA analysis was based on the assumption that outburst flood hazard is mainly linked to the expansion in lake area (irrespective of lake type) which can be detected via remote sensing technique.

Figure 3. In the arid environment, agriculture livelihood of the communities depends on ice-melt water from high mountain glaciers which are highly vulnerable to changing climate (Chitral basin, surveyed in 2013) (Photo courtesy: Imran Ahmad)

The Shuttle Radar Topography Mission (SRTM) DEM of 30m resolution was used for topographic analysis and developing snow avalanche and landslide (SAL) index based on slope classification. Although, slope instability is influenced by lithological formation and tectonics, but most of the lithological zones are complex of different rock types and tectonic setup, therefore slope factor is considered in this study as a major determining factor in landslide hazard. Slopes less than 30 degrees seldom produce avalanches and about 91% of the avalanches involved start zones between 30° and 45° (McCammon, 2009). According to Rahman et al. (2014), slope instability is directly proportional to slope gradient and landslide occurrence escalates with increase in slope gradient. Furthermore, the impact of slope gradient on landslide susceptibility was found maximum at slope ranging from 31 to 45 degrees. Highest weight was assigned to >30° slope class representing high SAL risk, while lowest weight was assigned to <15° slope class representing low risk owing to relatively safe sloppy condition (Table 1). During field surveys conducted periodically between 2007 and 2019, vulnerability of the local communities to climate-induced hazards and risks involved were investigated in the region.

Table 1. Indices of Glacier Depletion by Volume (GDV), Expansion in Lake Area (ELA) based on aggregate changes in glacial ice volume and lakes area during 2001-2013 period, and Snow Avalanche & Landslide (SAL) based on slope category in the HKH basins

Risk	GDV (km^3)	ELA (km^2)	SLA (deg)
High	>2.0	>4.0	> 30°
Moderate	<2.0	<4.0	15°– 30°
Low	No decrease	No increase	<15°

Results and discussion

Multi-hazard Risk assessment

The glaciated basins indicated variable changes in aggregate ice volume ranging from -8.5 km^3 in Astore basin to 4.5 km^3 in Shigar basin during 2001-2013 period. High risk of GDV was observed in the Astore and Swat river basins (Figure 4) likely because of combined effect of reduced precipitation and rising warm temperatures in these basins (Ren et al. 2006). A valley type glacier Chungphare (length~11.7 km) lying eastward of Nanga Parbat in Astore basin (Figure 5) has retreated over 600 m during 1934 to 2013 period (Nüsser and Schmidt 2016). The depleting glacier has highly influenced the melt-water supplies to the nearby Tarishing valley in the western part of this basin. Most of the basins exhibited positive change in ice mass during the 12-year period (Figure 4). The gain in ice volume was >2.0 km^3 in the Gilgit, Hunza, and Shigar basins of the Karakoram. A slight loss in ice mass observed in the Shyok basin of the Karakoram is likely because of the influence of growing anthropogenic activities under geopolitical situation across the basin. However, the ice reserves under <5 km^2 size category of glaciers appear to exceed 25 km^3 in this basin during 2013 period. The variations observed in glacial ice in different river basins may be attributed to factors like glacial mass balance, area-altitude distribution, debris cover and slope differences (Copland et al., 2011).

Overall the risk of GDV was found low in seven river basins (shown in Table 2). However, the accelerated down-wasting and retreat of some of the medium to large sized valley glaciers hamper the functionality of the kuhl irrigation systems in some of these basins. The retreat of Passu glacier had resulted in abandoning of the associated villages in its south owing to drying up of the kuhl system between 1950s and 1960s period in the upper Hunza valley (Figure 6). The inhabitants of the villages migrated to other places including nearby Ghulkin village (Parveen et al., 2015). Although various factors are influencing the changes in cryosphere (e.g. climate, valley orientation, mountain aspect, elevation, slope, and wind speed), but scientific studies and evidences are currently inadequate to confirm the changes like retreat or surge of the glaciers, and what would happened under changing conditions in future.

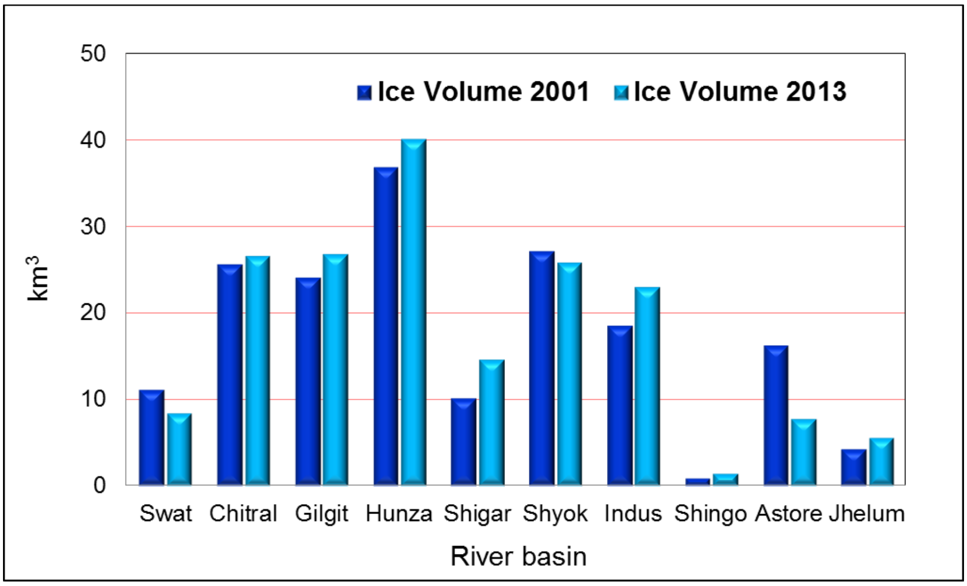

Figure 4. Temporal changes in glacial ice volume in different HKH basins during 2001-2013

Figure 5. A depleting glacier Chungphare, eastward of Nanga Parbat has highly influenced the melt-water supplies to nearby Tarishing valley in the Astore basin (2017)

Figure 6. The retreat of Passu glacier resulted in abandoning of its associated villages in the south owing to drying up of the kuhls (upper Hunza valley)

The glacial lakes exhibited expansion in area in most of the river basins indicating impact of growing warm conditions on glacial environment in this region (Figure 7). A faster rate of snow and ice melting under increased warm conditions usually causes formation and expansion of lakes in the Himalayan region (Bolch et al., 2012). The risk of expansion in lake area was high in the Indus sub-basin and moderate in the five river basins, i.e., Hunza, Shigar and Shyok in the Karakoram, and Shingo and Astore in the Himalaya range (Table 2). The significant changes in lake area in the Indus sub-basin, Shyok, Shigar, and Hunza basins may be contributed by glacier-fed lakes like supraglacial and end-moraine dammed that might have been formed/expanded owing to faster rate of snow and ice melting during the recent decades (Ives et al., 2010). The risk of ELA was low in four basins (i.e., Swat, Chitral, Gilgit and Jhelum) either due to expanding of lakes at lower rates or shrinking in extent under changing hydro-climatic conditions. However in several cases, flooding events take place from breaching of englacial or small supraglacial lakes (usually referred to as outbursting of glaciers) which are difficult to detect from conventional remote sensing application (Richardson, 2010; Ashraf and Rustam, 2020). Some of the examples are floods occurred in Chitral basin during 2003, 2007, 2010, 2011, 2013 and in Hunza basin during 2007 and 2008. Sometimes intense rainfall events cause outburst of high altitude lakes resulting in heavy flooding as happened during 1994 and 2010 in the Gilgit river basin. Much of the damage done during such GLOFs is related to the accompanying debris containing enormous sediments and boulders (Figure 8).

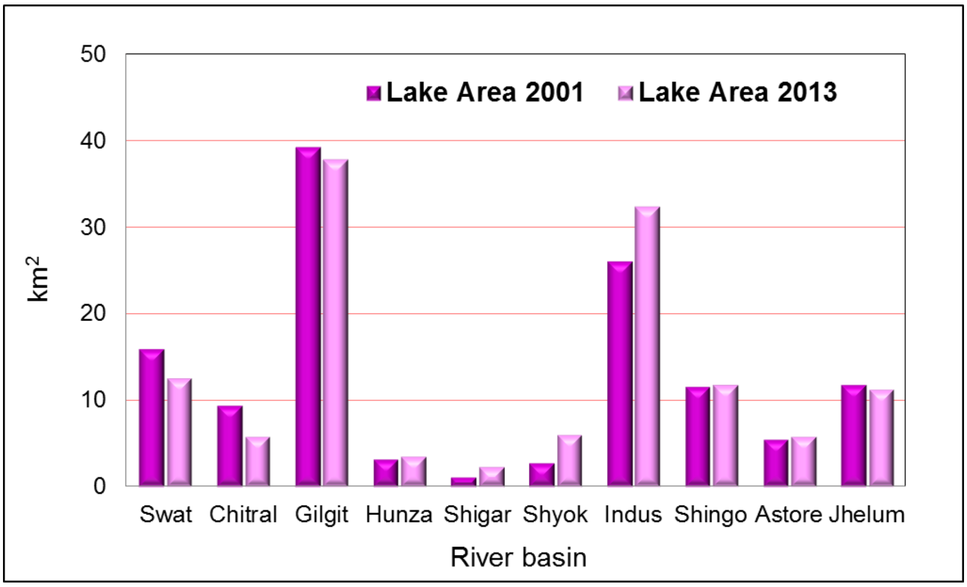

Figure 7. Variations in lake area in the HKH basins during 2001-2013

Figure 8. Irrigation infrastructure is highly vulnerable to flash floods that usually bring enormous sediments (Gilgit basin, surveyed in 2013)

Overall >2% area each of Hunza and Shigar basins of the Karakoram range exhibited high risk of avalanche and landslide hazard (Table 3). The Karakoram range is characterized by extensive landslide events that may be attributed to rapid rise of mountains, e.g. at rates ranging from <0.2 mm to >10 mm per annum (Zeitler, 1985) and high steep slopes. The occurrence of a disastrous landslide event on January 4, 2010 resulted in loss of numerous valuable lives, agriculture land and infrastructure in the Attabad village besides blockage of the Hunza river forming a large lake in the upstream (Figure 9). The lake subsequently engulfed parts of the mountain villages like Ainabad, Sheshkat, Gulmit, Ghulkin and Hussaini in the upper Hunza valley (Iqbal et al., 2014). The moderate SAL class (15°-30° slope) was observed dominant in >40% areas of the Chitral, Gilgit, Hunza and Shigar basins, while low risk of SAL (<15° slope) was found over >60% areas of the six river basins, i.e. Swat, Shyok, Indus, Shingo, Astore and Jhelum. However, occurrence of extreme events like earthquake, intense precipitation and flooding may intensify risks of snow avalanche and mass movement in these basins.

Figure 9. A catastrophic landslide event on January 4, 2010 resulted in loss of numerous valuable lives, property and infrastructure, besides blockage of the Hunza river near Attabad village forming a large lake in the upstream (2017)

Table 2. GDV and ELA indices indicating various risk levels in different river basins

Basin	GDV Risk	ELA Risk
Swat	High	Low
Chitral	Low	Low
Gilgit	Low	Low
Hunza	Low	Moderate
Shigar	Low	Moderate
Shyok	Moderate	Moderate
Indus	Low	High
Shingo	Low	Moderate
Astore	High	Moderate
Jhelum	Low	Low

Table 3. Percentage area under various risk levels of SAL index in different river basins

Basin	Area (km^2)	% High	% Moderate	% Low
Swat	14656	0.1	17.5	82.4
Chitral	15322	1.6	47.8	50.7
Gilgit	14082	1.6	44.5	53.9
Hunza	16389	4.5	49.1	46.4
Shigar	7382	2.1	47.0	50.9
Shyok	10235	1.8	37.8	60.3
Indus	32571	1.1	35.0	63.9
Shingo	4680	0.0	13.9	86.1
Astore	4214	1.3	36.8	61.9
Jhelum	9198	0.1	33.0	67

Risk mitigation strategies

The isolated nature of many communities coupled with fragile environment, high-altitudes and complex geological terrain of the UIB poses special constraints and challenges in risk mitigation of natural hazards. During field surveys, the farmers pointed the issues of disturbance in water flows for irrigation owing to glaciers fluctuation, conveyance loses, landslides/rock fall and climate change as also highlighted in several previous studies on this region (e.g. Butz, 1989; Parveen et al., 2015; Nüsser and Schmidt, 2016; Zulfiqar et al., 2019). Deforestation needs to be controlled in the river basins containing temperate, subtropical coniferous forest (e.g. in Chitral, Swat, Indus and Jhelum) because it leads to enhance warming, exaggerate glacier melting and land degradation in the region. Forest ecosystem can mitigate hazard impacts by serving as natural protective barriers or buffers against physical exposure to natural hazards such as landslides, floods, and avalanches (Dolidon et al., 2009; Kamble et al., 2013). In landslide prone areas, slope stabilization measures like improving slope drainage, planting vegetation and constructing retaining walls to support base of the slope should be promoted through involvement of the local communities. . In harsh climate and rugged terrains of the region, building of surface channels and sustaining water supplies are challenging for the communities (Figure 10). In such conditions, pipe-kuhl irrigation can improve the efficiency of transmission, maintain the water quality, avoid damages from landslides and reduce maintenance cost (SDPI, 2002; Ashraf and Iqbal, 2018). Generally flexible high-density polyethylene pipes are used either on ground surface or laid underground to ensure insulation and protection against extreme weather conditions for safe water supply. Partially or fully concrete system usually provides safe water supply throughout a season and reduces the time villagers spend on repairing channel to sustain the water flow (Hill, 2014). At places like in upper Hunza, owing to lack of water availability, farmers prefer to raise more drought-tolerant sea-buckthorn and poplar trees in their crop fields (Parveen et al., 2015).

The changes in water availability are also influenced by external development interventions and land use transitions (Nüsser et al., 2019). In parts of Swat and Indus sub-basin, the channel irrigation become vulnerable to depletion/drying of glacio-fluvial streams and springs owing to high urban development and socio-economic pressure. Such situations force the inhabitants residing in the upper reaches to shift down to lower valleys for their livelihoods. In the valleys alongside the rivers and perennial streams, water uplifting via solar system could be a viable option to ensure sustainability of agriculture and livelihoods. Appropriate measures can be adopted to revive the springs through provision of recharge facility like water ponds, ditches, semi-earthen channels, and managing glacio-fluvial streams via proper land use planning and in cases growing of glaciers in the upper reaches. An effective water governance system and site-specific water resource management have to be adopted as measures for future climate change adaptation in this region (IDRC, 2014). The adaptive capacity of the mountain communities is often hampered by limited access to financial and capital resources, isolation and fragility of the mountain ecosystems. Therefore, effective early warning mechanism, provision of adequate resources for preparedness and capacity building of the communities in advance water management techniques need to be ensured to cope with negative impacts of climate change in this region.

Figure 10. Sustaining melt water supplies via kuhl system is challenging in rugged terrain like of the Karakoram (Hunza basin, surveyed in 2017)

Conclusion

The cryosphere-fed irrigation system is highly vulnerable to extreme conditions like glacier depletion, glacial floods, snow avalanches and landslides that often disrupt channel flows. In this study, multi-hazard indexing approach was adopted to assess risk of climate change impacts in form of depletion of glaciers, critical expansion in lake area and snow avalanche, and landslide hazards on the cryosphere-fed kuhl irrigation system in the HKH region of Pakistan. High risk of glacial-ice depletion was observed in the Astore and Swat river basins likely because of rising warm temperatures and reduced snow precipitation in these basins. The risk of lakes outburst flood hazard was found high in the Indus sub-basin and moderate in the five river basins (i.e., Hunza, Shigar, Shyok, Shingo and Astore), while it was low in the rest of basins. However, occurrence of intense precipitation and extreme earthquake events may exaggerate risk of flash flooding in these basins. More than 2% areas of Hunza and Shigar basins in the Karakoram range exhibited high risk of snow avalanche and landslide (SAL) hazard, while moderate SAL hazard was found in >40% areas of Chitral, Gilgit, Hunza and Shigar river basins. As climate change is anticipated to have a significant impact on the behavior of glaciers and associated lakes that may ultimately trigger floods and landslides in the region, therefore, site-specific adaptation and management strategies need to be adopted under proper institutional setup in different river basins. Long-term monitoring of the hydrodynamics of glacial environment and effective risk management are essential to ensure sustainable agriculture development in this region in future.

Authorship contributions

A.A. conceived the idea, wrote and edited the main text and G.A. provided insight and suggestions to improve the discussion.

Conflict of interest

None

Acknowledgments

The technical and data support of Pakistan Meteorological Department (PMD) and International Centre for Integrated Mountain Development (ICIMOD) for executing this study is gratefully acknowledged. The database development and field support by Climate, Energy and Water Research Institute, National Agricultural Research Centre, Islamabad is also highly appreciated. We are thankful to the Editor and anonymous reviewers for rendering valuable comments and suggestions in improving this paper.

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