Evaluating Glacial Resource Sustainability for Mountain Irrigation in Pakistan

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Abstract

Glacial resource forms a significant source of freshwater for agriculture and economic development in the Upper Indus Basin (UIB) of Pakistan. The resource has become highly vulnerable to rapid changes in climate, coupled with the growing demand of water for multi-purpose use downstream in the region. In the present study, the sustainability of the glacial resource was examined for agricultural water management in the Hindu Kush, Karakoram and Himalaya (HKH) ranges of UIB through a glacial indexing approach. The indexing was based on the vulnerability of the glaciers by area and elevation to changing climate in the region. According to the index of glacier area, about 83.2% of glaciers belonging to <1 km^2 area class of glaciers indicated high vulnerability, 15.3% belonging to 1-10 km^2 class moderate vulnerability, and 1.5% of >10 km^2 class low vulnerability in the three HKH ranges. According to the index of glacier elevation, high vulnerability was observed in about 76.7% glaciers of the Hindu Kush, 40% of the Karakoram, 91% of the Himalaya, and overall 60% glaciers lying below 5000 m elevation in the HKH region. The sustainability of glaciers for kuhl irrigation system was observed good in about 24.3% glaciers and medium in 9.2% glaciers of the Hindu Kush range. The sustainability was good in about 61.9% glaciers and medium in 7% of glaciers of the Karakoram, whereas in the Himalaya it was good in about 9.6% glaciers and medium in 7.5% glaciers of the range. Overall, sustainability was found good in about 41.6% glaciers, medium in 7.6% glaciers and low in 58.8% glaciers of the HKH region. Integrated water resource management would help mitigate the negative impacts of climate and cryosphere change in the region. Long-term research on climate change and hydro-glacial dynamics would be important to understand the cryosphere response to changing climate and implications for water resource management in this region.

Keywords: Cryosphere, Glacier depletion, Indus Basin, Water management

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1. Introduction

The snow and glacial resources of the Hindu Kush-Karakoram-Himalaya (HKH) region feed the world's largest Indus irrigation system on which a large number of downstream communities depend (Lutz et al., 2016: Hasson et al., 2017; Wester et al. 2019). It contributes more than 50% of the total flows to the Indus River system and forms an important source of freshwater for irrigation, drinking, hydro-power and ecological balance in the region (ICIMOD, 2012). The region is warming at a rate higher than the global average over the last several decades (IPCC, 2019). The direct impacts of climate change are related to changes in the cryosphere which could ultimately affect the stream flows and irrigation potential in the HKH region (Scott et al., 2018; IPCC, 2019). The indirect impacts of climate change are increased risk of climate-induced hazards including floods, glacial lake outburst floods (GLOFs), snow avalanches, and debris flows (Bolch et al., 2012; Wang et al., 2015; Ashraf et al., 2021) that usually destroy irrigation infrastructure and agriculture land downstream (Richardson and Quincey, 2009; DRM, 2013; Wester et al., 2019). The glaciers in most of the HKH region are exhibiting retreating behavior (Pratap et al., 2015; Mir and Majeed, 2016; Azam et al., 2018), except central Karakoram where a slight positive ice mass balance is reported (Hewitt, 2005; Gardelle et al., 2012; IPCC, 2013; Farinotti et al., 2020; Nie et al., 2021; Wu et al., 2021). According to Nie et al. (2021), the dynamics of individual glacier surges in the Karakoram are out of phase, pointing towards a limited influence of climatic conditions in glacier surging behavior.

Water demand is increasing rapidly in the wake of growing urbanization, expansion in agricultural land and climate change (Kaser et al., 2010; Mukhopadhyay and Khan 2014; Gaddam et al. 2018). The meltwater of glaciers forms a major source of water intake by irrigation systems in most of the glaciated river basins (Nüsser and Schmidt, 2017; Ashraf and Ahmad, 2021). The vulnerability of the biophysical and socio-economic systems has increased because of the growing impacts of changing climate (IPCC 2019). Any reduction in meltwater flows may have significant implications for food security, hydro-power generation and socioeconomic development in the country. It is necessary to assess the potential of the glacial resource and vulnerability to changing climate for developing viable agricultural water management strategies for the region. The ground monitoring of the glaciers could be very accurate for the assessment of individual glacier characteristics and vulnerability to temperature warming but is difficult to perform in remote and inaccessible terrain of the Himalayan region (Ambinakudige, 2010; Kumar et al., 2021). Remote Sensing (RS) and Geographic Information System (GIS) provide an alternative method for the assessment of glacial resources and analyzing its spatio-temporal changes in the complex terrain of the HKH region (Zhao et al., 2020; Hayat et al., 2023).

The present study is focused on examining the sustainability of the glaciers in the Hindu Kush, Karakoram and Himalaya (HKH) region of Pakistan through a glacial indexing approach for future agricultural water management. The glacial indexing was based on the vulnerability of the glaciers by area and elevation to the changing climate in the region. Mountain *glaciers* are mostly susceptible to *temperature warming owing* to their relatively small size (Deng et al., 2019; Knight, 2022). The retreat of glaciers and loss of ice mass mainly accelerate below 5000 m elevation in the Himalayan region (Kulkarni and Alex, 2003).

2. Geographical setup

The study area stretches over 127,210 km^2 within the elevation range of <1000 m to >8000 m in the Upper Indus Basin of Pakistan. It comprises three major mountain ranges, i.e., the Hindu Kush over 32.3%, the Karakoram over 40.1% and the Himalaya over 27.6% of the area, which contain many small and large glaciers and glacial lakes (Fig. 1). About 4.7% area of the Hindu Kush, 20.3% of the Karakoram and 2.3% of the Himalaya are glaciated. This region with more than 7000 glaciers, along with Tibet and Pamir, is regarded as the *third* pole because of hosting a large glacial ice mass outside the polar *regions* (ICIMOD, 2011; *Nuimura* et al., 2015; Khan et al., 2022). Some of the renowned glaciers here include Baltoro, Batura, Biafo, Chiantar, Chogo Lungma, Hispar, Panmah and Siachen. The climate is predominantly warm continental/Mediterranean continental to humid sub-tropical and arctic/cold desert.

Large climatic diversity exists owing to high altitudinal differences and complex topography in the region. Major parts of the region in the north are out of monsoon reach due to high mountainous terrain. Annual rainfall ranging from 125 to 500 mm occurs mainly from the westerlies, monsoon and in a limited amount from the local thunderstorms (Ashraf and Akbar, 2020; Khan et al., 2020). The precipitation from westerlies forms the main source of snow accumulation that feeds glaciers at higher reaches of the region (Miller et al., 2012; Bocchiola ~~et al.~~ and Diolaiuti, 2013; Mölg et al., 2014). The valley bottoms are mostly drier than the higher elevations. October to March is characterized as low-flow months, and then the earliest supply of water is generated due to snowmelt from April/May to late July depending on the accumulated snow and concurrent temperatures (Hasson et al., 2014). The melting of glaciers starts in late June and continues till the end of September, depending on the melt season temperatures (Winston et al., 2013; Lutz et al., 2016). According to Archer (2003), the flows generated by snow/glacier melt during summer are mainly

controlled by energy input. Water supplies are generally managed through a cryosphere-fed irrigation system which supports the food security and livelihoods of the majority of the people living in this region (Ashraf and Ahmad, 2021; Tuladhar et al., 2023) (Fig. 2). The system is usually established using indigenous technology and local resources where sufficient meltwater flows are available for irrigation and domestic use. The efficiency of irrigation system is mostly influenced by the glacial meltwater flows which vary from season to season. For example, the meltwater inflows to the system are usually high during the summer months from June to September because of increased temperatures. The discharge of the channels may vary between 0.007 - 0.425 m^3/s, depending on the capacity of the system (Ahmad, 2008). Crop farming is generally practiced over less than two percent of land in the region, mostly engaged in subsistence agriculture. Being part of the India-Asia collision zone (Kazmi and Jan, 1997), the region has a complex geological history of tectonics, magmatism, metamorphism, uplift, erosional and depositional cycles, leading to the evolution of a variety of landform types such as mountains-valleys, weathered bedrock, gravelly fans, glacier moraines and alluvial valleys. The valleys are mostly unlevelled containing scattered, very shallow/moderately deep, slightly alkaline, gravelly and medium-textured soils (Soil Survey Report, 2006).

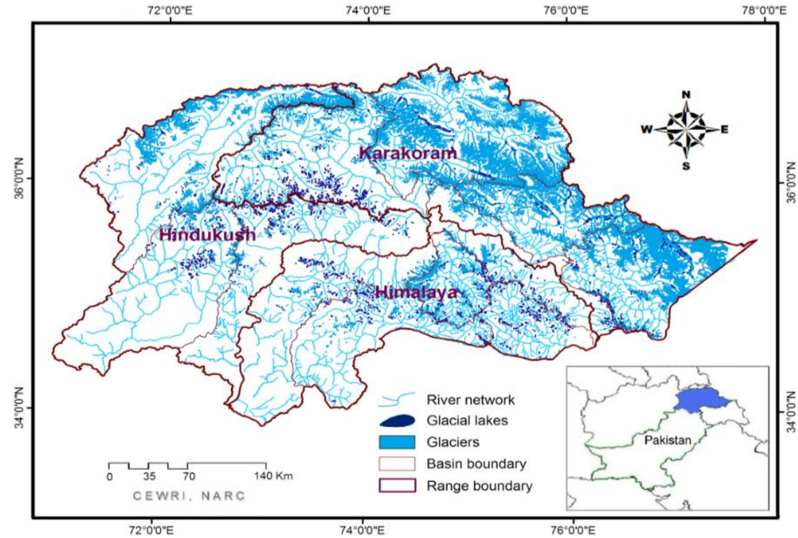

Figure 1. Glacial resource distribution in the HKH region of Upper Indus Basin, Pakistan (Ashraf and Iqbal, 2018).

Figure 2. Snow and glacial meltwater support mountain irrigation for sustaining agriculture in the region (Miar Peak in the upper left, Bagrot Valley).

3. Material and Methods

3.1. Data and methodology

Time-series data of rainfall and temperature of ten meteorological stations were collected from the Pakistan Meteorological Department (PMD) for the 1960-2019 period. The data were segregated and averaged into two climatic normals, i.e., 1960-1989 and 1990-2019 for change analysis. The glacier inventory data of ICIMOD (2011) and GIP (2017) were used to determine the physical characteristics of the glaciers, i.e., number, area, ice volume, in the region. The area–thickness relationship based on measurements of the glacial ice thickness in China's Tianshan Mountains was used to determine the volume of the glacier ice in the HKH region. According to the findings, glacial thickness increased with an increase in glacier area (LIGG et al., 1988). The relationship between ice thickness and glacier area was obtained using Equation 1.

$$H= -11.32 + 53.21A^{0.3} \qquad (1)$$

Where H is ice thickness in meters and A is glacier area in square kilometers.

This formula has been used for the estimation of mean ice thickness in several glacier inventories of the HKH (Chaohai and Liangfu, 1986; Mool et al., 2001; Roohi et al. 2005; Bajracharya and Shrestha, 2011). The ice volume is determined by multiplying the mean ice thickness and the glacier area. The DEM data, available at the NASA site www.jpl.nasa.gov/, was used to analyze the altitudinal dynamics of the glaciers. Ground data and information on agriculture, natural resources and socio-economic were collected through field surveys conducted in various parts of the region, communication with the local communities, and available literature/ reports.

Trend and change analysis of climate was performed for selected meteorological stations of the study area using time-series data of the 1960-2019 period. The vulnerability of the glaciers to climate change was assessed through developing indices of glacier area and elevation. According to Knight (2022), small-sized glaciers are more susceptible to temperature warming than large ones that are relatively stable and less vulnerable to climate change. For indexing of glaciers by area, the size categories of glaciers were defined after modification from Ashraf and Iqbal (2018). A maximum weight of 3 was assigned to glaciers having <1 km^2 area representing higher vulnerability to changing climate (Table 1). A weight of 2 was assigned to the 1–10 km^2 area class of glaciers representing moderate vulnerability and a weight of 1 to >10 km^2 class of glaciers representing low vulnerability of glaciers to climate change.

The glaciers indicated depletion at variable rates up to 5000 m elevation in the Asian mountains as a result of growing warm temperatures (Deng et al. 2019). The glaciers below 5000 m were assigned weight 2 representing high vulnerability, while the ones above 5000 m elevation were assigned weight 1 representing low vulnerability to climate change. The weights of the two vulnerability indices were multiplied to define the sustainability index of glaciers for the HKH region (Table 2). The final index classes were assigned ranks according to the sustainability of glacial resources for agriculture water management in the region.

Table 1. Vulnerability indices of glaciers by area and elevation.

Indices	Class	Weight	Vulnerability
Glacier Area (km^2)	<1	3	High
	1–10	2	Moderate
	>10	1	Low
Elevation (m)	<5000	2	High
	>5000	1	Low

Table 2. Sustainability index of glaciers for mountain irrigation in the HKH region.

Sustainability	Weight multiply	Rank
Good	<4	1
Medium	4	2
Low	6	3

4. Results and Discussion

4.1. Climate data analysis

Mean annual rainfall indicated an increase from 670 to 686 mm (2.4%) in the Hindu Kush, 210 to 281 mm (33.8%) in the Karakoram and 737 to 798 mm (8.3%) in the Himalaya range during the 1960-2019 period. The fact of the positive trend in rainfall in this region is also reported in several previous studies (Shekhar et al., 2010; Bolch et al., 2012; Chaudhry, 2017; Ashraf and Batool, 2019). Chaudhry (2017) reported 25% increase in the average annual rainfall and 18–32% in the summer rainfall over the core monsoon region of Pakistan during the last century. The annual rainfall trends were observed positive at most of the climate stations except at Drosh, Chilas and Astore during the 1960-2019 period (Fig. 3). Generally, topographic and atmospheric interactions control the distribution of precipitation in the region (Bookhagen and Burbank, 2010; Immerzeel et al., 2014). The R (define R) values were positive at Gupis for all months except May and December. At Gilgit, R values were positive for all months except April, May, July and October. At Bunji and Skardu, R values were negative for March, May and October months only. At Chitral, the values were observed as negative for March, April, May, September and December during the 1960-2019 period. Latif et al. (2018) reported an increase in winter precipitation in this region during the 1961-2013 period. The increase in precipitation may cause hazards like flash floods, debris flows and landslides that could harm agriculture land and infrastructure downstream.

The annual mean temperature was observed at 16.7°C in the Hindu Kush, 14.1°C in the Karakoram and 14°C in the Himalayan range during the 1990-2019 period. The mean temperature indicated variable rising trends at the selected meteorological stations during this period. The mean annual area-weighted temperature of Gilgit-Baltistan exhibited an increasing trend during the 1901-2014 period (Ashraf and Batool, 2019). The increase in air temperature may lead to liquid precipitation instead of snow formation and higher rates of evapotranspiration in this region. The rise in warm temperatures and precipitation generally exaggerates the ice melt rate at lower elevations (Bliss et al., 2014).

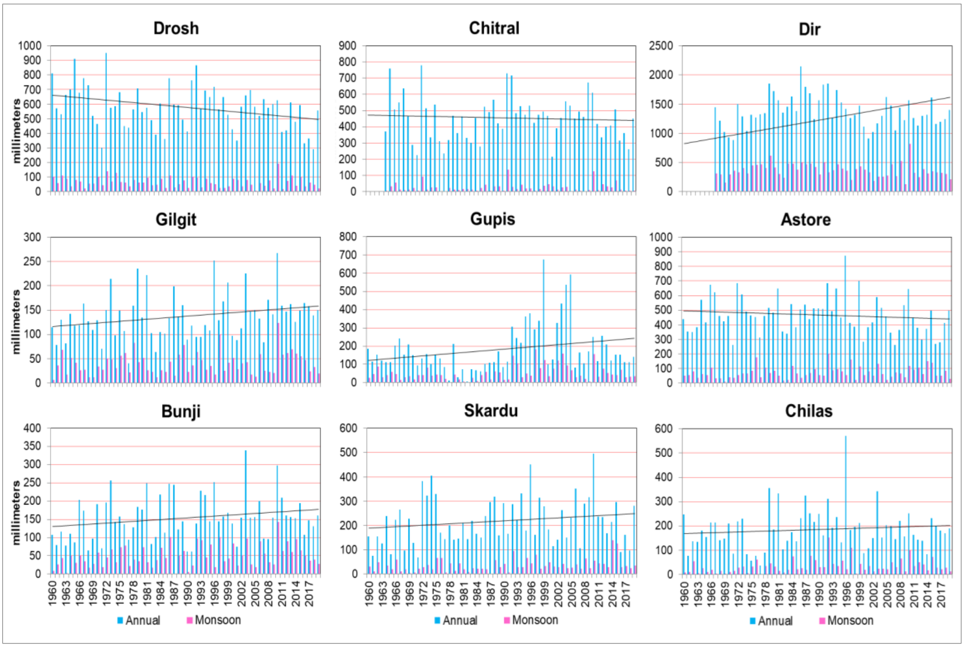

Figure 3. Annual rainfall trends at selected stations in the study area during 1960-2019 period.

4.2. Glacial Resource Analysis

Of the total of 7422 glaciers, 22.9% occur in the Hindu Kush, 54.8% in the Karakoram and 22.3% in the Himalaya range of the country. About 14.7% glaciated area is shared by the Hindu Kush, 79.1% by the Karakoram and 6.2% by the Himalaya. Most of the glacial coverage is shared by the Karakoram basins such as Hunza, Shigar and Shyok, while the minimum glacier area is in the Himalayan basins like Shingo and Jhelum (Fig. 4). The possible reasons for higher glacial ice mass in the Karakorum may include increased precipitation, a consistent decline in local summer temperatures and the presence of thick debris cover over the glacial surface (Hewitt, 2005; Fowler and Archer, 2006; Mishra, 2015). Relatively less ice mass, coupled with the presence of extensive meltwater in the form of lakes, point towards a high influence of temperature warming in the Hindu Kush and Himalaya basins (Fig. 4). In the Hindu Kush, about 63 km^3 of ice volume is shared by a 10-50 km^2 area class of glaciers (Table 3). About 48.2 km^3 of ice volume is shared by 100-500 km^2 area class and 30 km^3 by 50-100 km^2 area class of glaciers. A total of 86% of glaciers of <1 km^2 class contribute 5.6% ice volume only, while 11.5% of glaciers of 1-5 km^2 class share 11.4% ice volume in this range. In the Karakoram, a maximum of about 795.3 km^3 ice volume is shared by >500 km^2 class of glaciers. About 631.5 km^3 ice volume is shared by 10 glaciers of 100-500 km^2 class and 185.6 km^3 by 71 glaciers of 10-50 km^2 area class. In total, 78.9% glaciers of <1 km^2 class contribute 1.3% ice volume only, while 16.3% glaciers of 1-5 km^2 class share 4% ice volume in this range. In the Himalaya, about 34% ice volume is shared by the 1-5 km^2 area class, 33% by the 10-50 km^2 area class and 11.7% by the 5-10 km^2 area class of glaciers. A total of 90.5% glaciers of <1 km^2 class contribute 21.3% ice volume in this range (Table 3). Overall, in the three HKH ranges, about 36.4% ice volume is shared by the >500 km^2 class, 31.1% by the 100-500 km^2 class and 12% by the 10-50 km^2 area classes of glaciers.

Table 3. Physical characteristics of the glaciers in the HKH region of Pakistan.

Area class (km^2)	Hindu Kush			Karakoram			Himalaya		
	Number	Area (km^2)	Volume (km^3)	Number	Area (km^2)	Volume (km^3)	Number	Area (km^2)	Volume (km^3)
<0.1	357	21.16	0.26	722	41.18	0.48	519	28.55	0.32
0.1-0.2	409	58.05	1.06	797	112.84	2.05	390	53.53	0.96
0.2-0.4	387	107.97	2.69	878	246.30	6.11	326	89.94	2.22
0.4-0.6	168	81.11	2.53	410	197.66	6.12	145	71.32	2.23
0.6-0.8	103	71.50	2.58	244	167.32	5.96	71	49.03	1.75
0.8-1.0	46	41.07	1.63	158	139.70	5.49	45	39.93	1.57
1.0-5.0	194	387.95	21.84	664	1377.82	78.25	143	266.87	14.46
5.0-10	30	208.60	17.53	95	628.26	51.74	9	60.15	4.95
10-50	4	502.25	63.00	71	1480.62	185.55	6	117.13	14.00
50-100	2	161.58	30.07	15	1030.87	183.04	-	-	-
100-500	1	196.56	48.22	10	2350.74	631.50	-	-	-
>500	-	-	-	3	2145.76	795.26	-	-	-
Total	1701	1837.8	191.39	4067	9919.06	1951.56	1654	776.47	42.46

The glacial resource indicated variable concentration over different elevations. It exists mainly within the elevation range from 2409 m to 8566 m in the UIB, the lowest in the Hunza basin and the highest in the Shigar basin of the Karakoram range. In the Hindu Kush, about 64.5% of ice volume was found within the 4000-5000 m elevation range, 34.4% within 5000-6000 m, and 0.9% within the 6000-7000 m elevation range (Table 4). In the Karakoram, a maximum of about 56.6% ice volume was observed within the 5000-6000 m elevation range, followed by 43.1% within the 4000-5000 m and 0.2% within the 6000-7000 m range. The Himalaya exhibited 81.7% ice volume within 4000-5000 m elevation and 15.2% within the 5000-6000 m elevation range. Overall, a maximum of about 58.6% of glaciers were identified within 4000-5000 m and 53.9% of ice volume was assessed within the 5000-6000 m elevation range in the three HKH ranges. According to ICIMOD (2011), about 59% of the glacier area exists within the 4800-5800 m elevation range in the Indus basin.

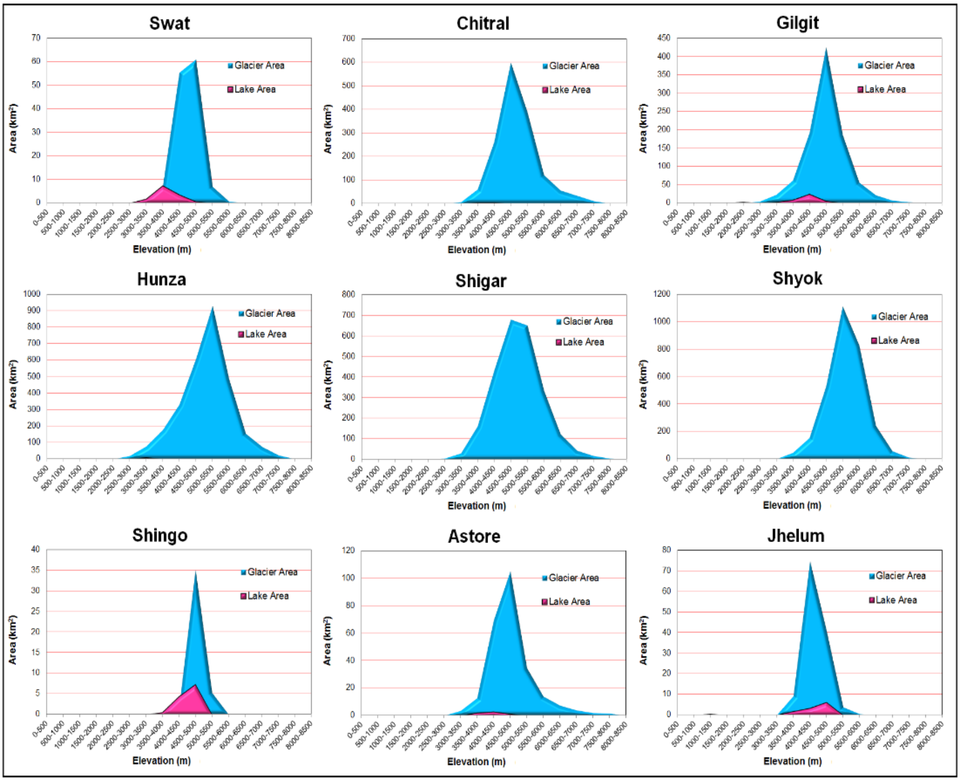

Figure 4. Glacial resources in different river basins of the HKH region.

Table 4. Percentage distribution of glaciers in different elevation zones of the HKH ranges.

Elev. Zone (m)	Hindu Kush			Karakoram			Himalaya		
	Number	Area	Volume	Number	Area	Volume	Number	Area	Volume
>7000	0.1	0.1	0.1	0.2	0.0	0.0	0.1	0.5	0.5
6000-7000	2.5	1.9	0.9	4.2	0.8	0.2	0.4	0.7	0.6
5000-6000	20.7	31.2	34.4	56.0	52.3	56.6	8.8	13.2	15.2
4000-5000	74.5	66.2	64.5	39.4	46.6	43.1	89.3	83.9	81.7
<4000	2.2	0.6	0.2	0.1	0.3	0.1	1.5	1.7	2.1
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

4.3. Vulnerability analysis of the glaciers

The vulnerability of the glaciers was examined through analysing indices of glacier area and elevation which have key role in glacial melting under growing temperature warming in the region. The vulnerability was observed high in about 86.3% glaciers belonging to the <1 km^2 class and moderate in 13.3% glaciers belonging to the 1–10 km^2 class in the Hindu Kush range. The former glaciers constitute about 10.74 km^3 ice volume and the later 39.37 km^3 ice volume. The high-altitude small-sized glaciers form a significant source of freshwater supply for irrigation and domestic use in the Hindu Kush range (Fig. 5). Low vulnerability was observed in about 0.4% glaciers of >10 km^2 class in the Hindu Kush, which contain a maximum of about 141.29 km^3 ice reserves owing to the presence of several valley glaciers. In the Karakoram range, vulnerability was found high in about 78.9% glaciers, moderate in 18.7% glaciers and low in 2.4% glaciers constituting about 26.21 km^3, 130 km^3 and 1795.35 km^3 ice volume respectively. In the Himalaya, about 90.4% glaciers were observed highly vulnerable and 9.2% moderately vulnerable constituting 9.06 km^3 and 19.41 km^3 ice volume respectively in the Himalayas. Although the low vulnerability was found in about0.4% glaciers only in this range, they contain about 14 km^3ice reserve. Overall, 83.2% glaciers indicated high vulnerability, 15.3% moderate vulnerability and 1.5% low vulnerability constituting about 46.01 km^3, 188.77 km^3 and 1950.63 km^3 ice volume in the three HKH ranges, respectively. About 76.7% glaciers of the Hindu Kush, 40% of the Karakoram and 91% of the Himalayas range were found highly vulnerable because of lying at <5000 m elevation. According to Xie et al. (2023) and Bonekamp et al. (2019), the surface area of glaciers is lost below 5000 m elevation owing to the influence of temperature warming in the region. Overall, about 60% glaciers were identified as highly vulnerable based on the index of glacier elevation in the HKH region.

4.4. Sustainability analysis of glaciers

The sustainability of the glaciers was investigated based on the combined effect of the glacier area and elevation in the three HKH ranges. The sustainability was observed as good in about 24.3% glaciers constituting 81.8% ice volume and medium in about 9.2% glaciers having 14% ice volume in the Hindu Kush range (Fig. 6). Here low sustainability was observed in about 66.4% glaciers constituting 4.2% ice volume only. The depletion of small glaciers in this range could disturb seasonal meltwater flows which are important in sustaining agriculture and livelihoods of the large number of communities residing downstream. The sustainability of glaciers was found good in about 61.9% glaciers constituting

96.6% ice volume and medium in 7% glaciers having 2.9% ice volume in the Karakoram. This range contains several large-sized valley-type glaciers with thick debris cover over their lower surfaces near the terminus (Fig. 7). The debris cover has an insulating effect which plays an important role in modulating glacier melting under climate change (Dobreva et al., 2017; Nabi et al., 2022). The unique topography and climatic conditions of the Karakoram contribute to its distinct glacier characteristics, setting it apart from other mountain ranges (Morton, 2011). The low sustainability was observed in about 31.1% glaciers of the Karakoram, which constitute 0.5% of ice volume only. In contrast, sustainability was found good in about 9.6% glaciers and medium in about 7.5% glaciers of the Himalaya. The former glaciers constitute about 43.9 km^3 ice volume and the later 36.5 km^3 ice volume. The sustainability was observed low in the majority of the glaciers in the Himalaya (i.e., 83% with ice volume of about 19.6%) because of having small size and <5000 m altitudinal location. Overall, the sustainability of the glaciers was found good in about 41.6% glaciers constituting about 94.3% ice volume in the HKH region (Fig. 6). Medium sustainability was observed in about 7.6% glaciers containing 4.5% ice reserves and low sustainability in about 58.8% glaciers having 1.2% ice reserves in the region. The low sustainability found in the glaciers could create high risk of disturbance in seasonal meltwater flows for the downstream irrigation system.

Figure 5. High-altitude glaciers form a major source of water supply for local communities in the Hindu Kush range (Bindo Gol glacier, Chitral Basin).

Local communities are adopting various measures to cope with the challenges of climate and cryosphere change. For example, in the case of diminishing meltwater flows for irrigation systems owing to glacier depletion, they are attempting to pump water from lower altitude points of water input from glaciers to the high altitude water channel. In places, meltwater is managed through a pipe-flow system to avoid disturbances in the flows owing to increased risks of flash floods and landslide hazards. The irrigation channels lined or replaced with pipes help minimize conveyance losses that sometimes exceed 30 percent in the region (Sarfraz and Ahmad, 2016). The melt characteristics of the debris-covered glaciers and the changing behavior of the glaciers with orientation and slope are necessary to understand better water resource management in the region. The rise in temperatures during the ablation period may cause extended shrinkage of the glaciers, however, the increase in the winter precipitation will contribute to snow/ice storage in the region. It is essential to understand the relationship between temperature and the hydrological cycle to comprehend the potential impact of warming trends on precipitation patterns (Fallah et al., 2024). As compared to degraded ecosystems, healthy ecosystems recover more efficiently and provide more resilience to the negative impacts of climate change (IPCC 2011). There is a need to launch afforestation/reforestation programs to help absorb extreme climate-induced hazards through improving ecosystem health in the region.

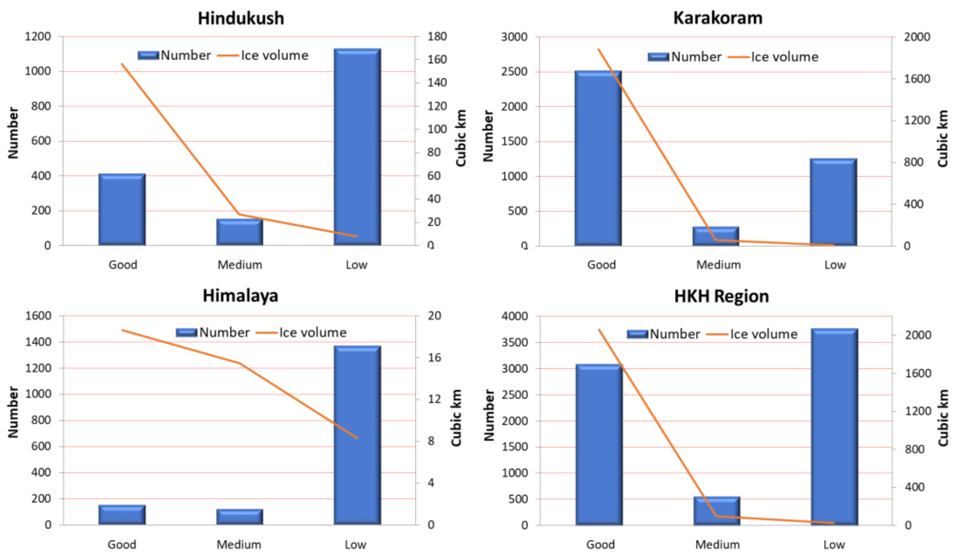

Figure 6. Sustainability analysis of glacial resources in the HKH region.

Figure 7. Valley glaciers are mostly debris-covered in the Karakoram region.

5. Conclusion

In the present study, the sustainability of the glacier resource was evaluated based on indexing of glacier area and elevation in the HKH region of Pakistan for future agriculture water management. The findings of the study indicated a rising trend in mean annual precipitation and temperatures in the HKH region. According to the index of glacier area, about 83.2% of glaciers belonging to <1 km^2 area class of glaciers indicated high vulnerability, 15.3% belonging to the 1-10 km^2 class moderate vulnerability and 1.5% of >10 km^2 class low vulnerability in the three HKH ranges. According to the index of glacier elevation, a high vulnerability was observed in about 76.7% glaciers of the Hindu Kush, 40% of the Karakoram, 91% of the Himalaya, and overall 60% glaciers lying below 5000 m elevation in the HKH region. The sustainability of glaciers for the kuhl irrigation system was found good in about 41.6% glaciers, moderate in 7.6% glaciers and low in 58.8% glaciers of the three HKH ranges. The complex nature of glacier dynamics in the Karakoram underscores the importance of considering various factors, such as glacier morphology and internal processes. Any change in the glacial resource may significantly impact the food security, energy demand and ecosystem diversity in the country. Therefore, an integrated water resource management approach would help mitigate the negative impacts of climate and cryosphere change, and enhance agriculture productivity in the region. The glacial system, including glaciers and lakes, should be declared protected to restrict unlawful human interruptions, conserve the freshwater ecosystem and avoid any risk of glacial hazard downstream. The region lacks a sufficient number of high-altitude automatic weather stations (i.e., above 4000 m) that are needed to get an insight into the distribution and magnitude of precipitation and temperature warming at higher elevations. Regular monitoring of the snow and glacial cover is necessary to assess the glacial mass balance and its implications on the hydrological budget of the region.

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