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Climate-induced Glacial Lake Outburst Floods and Nature-based Risk Management Approach in the Upper Indus Basin, Pakistan

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Abstract

The glaciated region of the Upper Indus Basin (UIB) has become highly vulnerable to rapid changes in climate, coupled with the region's need for sustainable development. The increase in the frequency of climate and flooding-related calamities in recent decades demands more proactive strategies to combat floods and other extreme weather disasters in the region. This paper focuses on evaluating climate dynamics, GLOF risks, and nature-based risk management strategies for sustainable development in the Hindu Kush, Karakoram, and Himalaya (HKH) region of the UIB, Pakistan. The mean annual rainfall exhibited an increase from 670 to 686 mm (2.4%) in the Hindu Kush, from 210 to 281 mm (33.8%) in the Karakoram, and from 737 to 798 mm (8.3%) in the Himalaya range during the 1960-2019 period. The majority of glacier-fed lakes in the Karakoram and Himalaya indicated an expansion in lake area. Climate change has influenced the cryosphere regime, leading to the frequent occurrence of flash floods/GLOF events resulting in environmental degradation, loss of infrastructure, property, and valuable lives downstream. Effective nature-based flood risk management needs to be promoted by preserving the natural ecosystem, enhancing its health, and strengthening the response capacity of vulnerable communities in the region. Launching afforestation and reforestation projects might help absorb shocks from flood hazards, reduce flood runoff, sediment loads, and socio-economic susceptibility. It is essential to promote good practices of NBS in flood risk management through raising awareness, demonstration, and initiating educational programs. Capacity building of local communities and institutions through resource sharing, skills transfer, and enhanced knowledge dissemination is crucial to improve flood risk mitigation in vulnerable areas of the region. For effective GLOF risk management, local communities must be involved in the development of NBS measures at the policy level.

Keywords

Ecosystem health; Glacier melting; GLOF; Karakoram; Indus basin

1. Introduction

The snow and glacier reserves of the Hindu Kush-Karakoram-Himalaya (HKH) region feed the world's largest Indus irrigation system, on which over 200 million people rely downstream [1-4]. Over the past few decades, the HKH region has warmed more rapidly than the worldwide average [5]. The severe consequences of global warming include an increase in glacier melting, the expansion of associated lakes, and an alarming rate of glacial lake outburst flood

(GLOF) incidents in the HKH region. Most glaciers in the HKH region are retreating [6-8], except in central Karakoram, which shows a slight positive ice mass balance [9-13]. Glacial lakes have formed and expanded as a result of glacier melting [14-16]. This could abruptly result in a glacial lake outburst flood (GLOF) releasing millions of cubic meters of water and debris (peak flows as high as 15,000 m^3), which may severely damage property and infrastructure, and result in the loss of valuable lives [17-19]. On average, GLOF events occur every three to ten years and have varied socioeconomic effects in the Himalayan region [20]. Over 15 million people worldwide are at risk of being impacted by possible GLOFs, and about 9.3 million of those live in the high mountain regions of Asia, including Pakistan, which contains a high concentration of lakes [21, 22].

The Sendai Framework for Disaster Risk Reduction (SFDRR) highlighted the necessity of implementing national plans as soon as possible to adequately protect the population, particularly in developing countries [23]. The significance of ecosystem management for Disaster Risk Reduction (DRR) has grown since the adoption of the Sendai Framework 2015–2030 [24]. Pakistan is among the countries most affected by extreme climate-related disasters [25]. The frequency of GLOF events has increased in the country as a result of rapid changes in climate over the last several decades [26]. Agricultural land, infrastructure, and settlements lying close to glacial lakes and along exposed riverbeds are particularly vulnerable and at risk. Communities living in mountain valleys prone to GLOFs are highly vulnerable, and vulnerabilities are compounded by poverty, mounting demands on natural resources, high-risk settlement patterns, and the need for increased knowledge, awareness, and education to lower the risk from GLOF events [27]. The increasing effects of climate change have made the biophysical and socioeconomic systems more vulnerable [5, 28].

Although causes and characteristics of GLOF hazards have been frequently studied in detail [29-32], knowledge and understanding of economically viable and socially acceptable drivers of risk mitigation are lacking [33, 34]. It is hypothesized that an NBS approach can be effectively adopted for GLOF risk management and building resilience of the communities against the negative impacts of climate change in this region in the future. This paper is focused on evaluating climate change dynamics, GLOF risks, and nature-based risk management strategies for sustainable development in the HKH region of the Upper Indus Basin (UIB), Pakistan.

1.1 Geographical setup

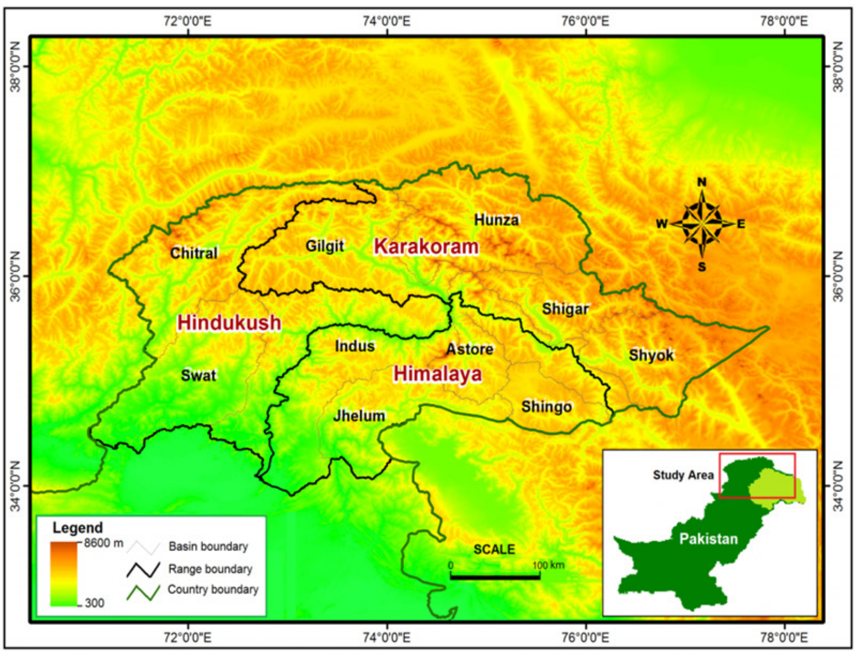

Figure 1. Location of three HKH ranges in northern Pakistan.

The study area stretches over 121,724 km^2 in the UIB of Pakistan (Figure 1). It comprises 32.3% of the Hindu Kush, 40.1% of the Karakoram, and 27.6% of the Himalaya range. Many glaciers and glacial lakes are found in these mountain ranges, ranging in elevation from less than 1000 m to over 8000 m. The climate is predominantly warm continental/Mediterranean continental to humid subtropical and arctic/cold desert. Annual rainfall ranges from 125-500 mm, contributed by westerly winds, monsoons, and local thunderstorms [35]. Winter precipitation occurs between October and March due to westerly winds originating from the Mediterranean and the Caspian Sea, while summer precipitation during July-September is usually received from the monsoon originating from the Bay of Bengal [36]. Precipitation from westerly winds is the main source of snow accumulation that feeds glaciers in the higher reaches of the region [37-39]. The melting period of seasonal snow is from April to June, while the melting of glaciers starts in late June and continues until September [3, 40]. The annual mean temperature was 16.7°C in the Hindu Kush, 14.1°C in the Karakoram, and 14°C in the Himalaya range during the 1990-2019 period. Agriculture, livestock, and tourism are the key drivers of the local economy. Economic development is progressing slowly in the region due to a limited resource base and inadequate communication infrastructure. Overall, the villages have an agro-pastoral livelihood. Summer is the main agricultural season when cereal and vegetable crops are grown, fruits are harvested and stored, and livestock are moved to alpine-style pastures at high elevations for grazing.

2. Data and Methodology

Rainfall and temperature data (maximum and minimum) from ten stations spanning 1960–2019 were obtained from the Pakistan Meteorological Department (PMD). The source data of glacial lakes were acquired from the lake inventory of 2013 [26], in which a spatial database of lakes, including location coordinates, area, and length, was systematically developed, and analysis was performed for each river basin in a GIS environment. The lakes were classified into various types: erosion, cirque, valley, end-moraine dammed, lateral-moraine dammed, supraglacial (lake on the surface of a glacier), and blocked, according to their physical characteristics. Field surveys were carried out to assess the risk of GLOF hazard in response to changing climate in vulnerable areas of the region.

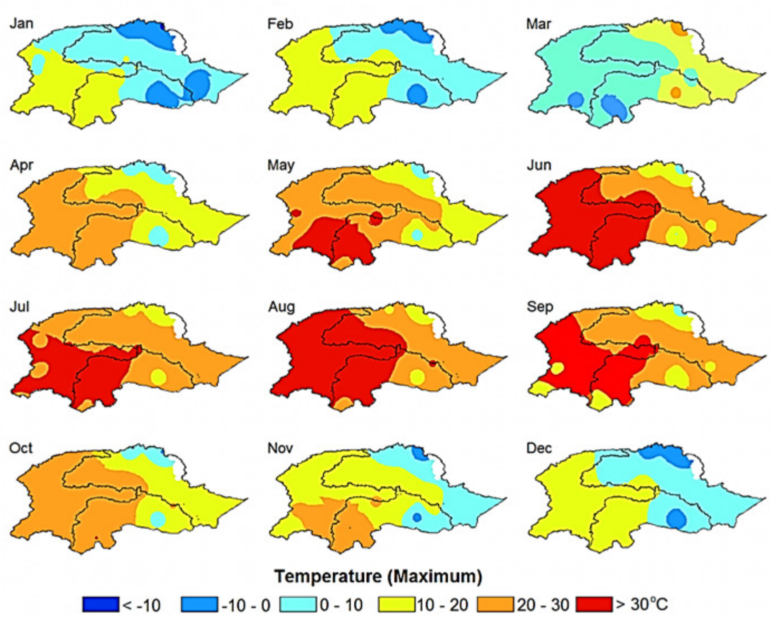

Figure 2. Spatial variability in mean monthly T_{max} in the HKH region.

Trend analysis of climate data was performed for selected meteorological stations of the UIB for the 1990-2019 period. The climate data was categorized into two climate normals, i.e. 1960–1989 and 1990–2019, for change analysis in the Hindu Kush, Karakoram, and Himalaya ranges. Mean monthly temperature data was mapped to analyze spatial variability in the region. The mean maximum temperature was found between 20 and 30°C during April-October and over 30°C during May-September in different parts of the study area (Figure 2). It ranged between 34°C and 39°C during May-September, highest in the month of July followed by 38.2°C in August and 37.1°C in June. During winters, the temperature varied between 18 to 23°C, former in the month of January and the latter in the month of March. In certain northern and eastern regions of the study area, temperatures ranging from -10°C to 0°C were recorded in isolated locations between November and March. The variation in temperature shows a large influence of the topography of the High Himalayan mountains. The mean lowest temperature was between 20 and 30°C from June to September and greater than 10°C from April to October in different regions of the study area (Figure 3). It ranged between 19 and 27 during months from May to September, highest in the month of July followed by 26.1°C in the month of August. Archer [41] asserts that energy input primarily regulates the flows produced by summertime snow and glacier melt. Low-flow months are October through March, and depending on the amount of snow that has accumulated and the temperatures at the time, the earliest supply of water is produced by snowmelt from late May to late July [42]. During winter months (December to March), it varied between 6 to 9.7°C, former in the month of January and the latter in the month of March, especially in the lower parts of the study area. Pockets of <10°C temperature were found in parts of the Karakoram and Himalaya ranges during the November to March period.

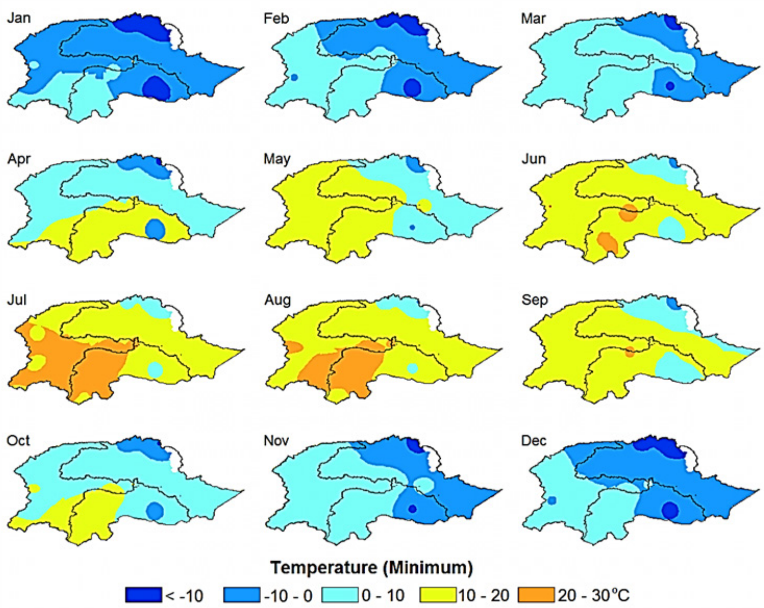

Figure 3. Spatial variability in mean monthly T_{min} in the region.

Mean summer temperatures (April–September) ranged between 10 and 20°C in the majority of the middle and northern valleys, while it was between 20 and 30°C in the southern valleys. Mean annual rainfall was observed to be greater than 500 mm at Drosh, Dir, and Astore, and between 200-500 mm at Chitral and Skardu, while it was less than 200 mm at other stations during the 1960-2019 period (Table 1). The mean monthly rainfall was found to be higher during the Mar-May period at the selected stations likely because of the dominance of westerlies in this region. The maximum monthly rainfall was 226 mm at Dir during March, 109 mm at Drosh during April, and 103 mm at Chitral during the month of March. The flowchart of the methodology followed in this study is shown in Figure 4.

Table 1. Mean monthly and annual rainfall at selected stations in the UIB during 1960-2019 period

St/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Drosh	45.5	74.6	110.2	108.6	62.7	17.9	21.1	20.3	22.5	30.8	29.5	35.6	579.2
Chitral	42.1	71.0	103.3	84.5	41.6	8.5	6.7	6.5	11.4	20.6	25.8	33.5	455.0
Dir	107.1	176.4	225.6	170.2	88.7	55.4	141.5	145.5	78.7	65.4	57.5	68.9	1380.8
Gilgit	4.4	7.5	12.1	23.9	26.0	9.6	14.8	15.6	9.7	6.2	3.4	4.3	137.4
Gupis	6.9	12.5	15.2	37.0	27.3	16.1	15.9	22.9	12.3	7.7	2.9	5.3	181.9
Astore	36.0	46.2	73.4	84.0	64.0	25.2	23.7	23.8	24.0	22.3	17.9	27.0	927.8
Bunji	5.7	9.4	13.9	23.8	26.7	9.7	16.4	20.1	13.0	7.1	3.4	4.7	153.9
Skardu	25.1	28.4	35.7	30.3	25.4	10.3	9.5	13.6	12.4	6.5	5.8	15.1	217.9
Chilas	10.6	16.5	28.5	35.0	28.9	9.5	11.5	14.3	8.0	8.1	5.9	9.1	185.8

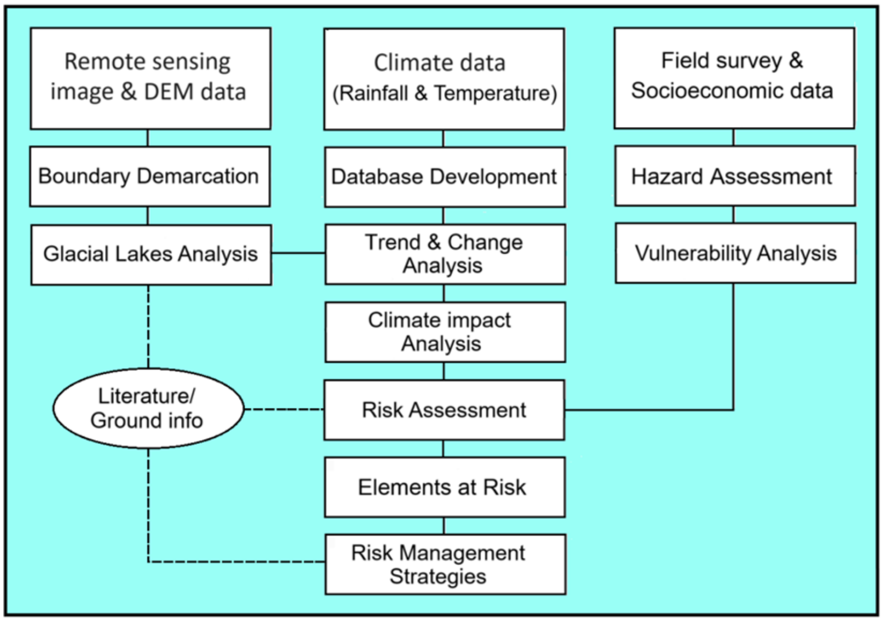

Figure 4. Flowchart of methodology followed in the present study.

3. Results and Discussion

3.1 Climate trend analysis

Annual rainfall trends were observed to be positive at five stations, namely Gilgit, Gupis, Bunji, Skardu, and Chilas, as indicated by the positive R values at these stations (Table 2). The R values were high for rainfall at the Gupis and Gilgit stations. Atmospheric and topographic interactions play a crucial role in precipitation distribution in the high-altitude HKH region [43, 44]. Monthly rainfall trends were found to be positive for most months at the Gupis, Bunji, Skardu, Gilgit, Chilas, and Chitral stations. The rising trends of rainfall at different stations are likely due to increased air temperatures leading to the conversion of solid precipitation (snow) into liquid precipitation. Several earlier studies have documented the positive trend of rainfall in this region [1, 15, 45-47]. The mean maximum temperature of summer (April-September) and winter (October-March) indicated rising trends mainly in the lower valleys comprising Swat, Jhelum, and the Indus sub-basin of the UIB. According to Fowler and Archer [48], the time series data of Gilgit and Skardu demonstrate a cooling trend in the summer months due to a drop in the minimum temperature and a warming trend in the winter months due to a rise in the maximum temperature.

Table 2. Monthly and annual rainfall trends indicative from coefficient of correlation R values at selected stations during 1960-2019

St/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Drosh	0.01	0.22	-0.22	-0.47	-0.28	0.12	-0.03	-0.06	-0.20	-0.01	0.17	-0.23	-0.34
Chitral	0.15	0.21	-0.16	-0.28	-0.18	0.15	0.03	0.15	-0.01	0.04	0.26	-0.20	-0.07
Dir	-0.09	0.12	-0.11	-0.05	-0.07	0.23	0.02	-0.09	-0.20	0.11	0.24	-0.21	-0.05
Gilgit	0.06	0.16	0.01	0.00	-0.01	0.42	-0.03	0.10	0.25	-0.04	0.32	0.08	0.26
Gupis	0.15	0.18	0.17	0.14	0.00	0.17	0.10	0.24	0.09	0.16	0.27	-0.02	0.27
Astor	-0.07	-0.10	-0.25	-0.14	-0.15	0.28	0.10	0.10	0.15	-0.13	0.18	0.03	-0.25
Bunji	0.23	0.21	-0.15	0.09	-0.09	0.27	0.09	0.15	0.27	-0.13	0.18	0.06	0.22
Skardu	0.11	0.19	-0.08	0.12	-0.12	0.20	0.01	0.24	0.27	-0.07	0.08	0.08	0.18
Chilas	0.08	0.23	-0.10	0.02	-0.05	0.20	0.05	0.16	0.21	-0.15	0.21	-0.01	0.11

In the Hindu Kush range, the mean annual rainfall showed an increase from 670 to 686 mm in this range during the 1960-2019 period. The >1000 mm rainfall range indicated a decrease from 30.2 to 29.7%, and <250 mm from 17.8 to 8.3% in coverage, while the 500-700 mm range exhibited an increase from 23.9 to 27.7% and 250-500 mm from 18.6 to 24% in coverage (Figure 5). The temperature range 10-15°C exhibited an increase from 13.8 to 15.5% and 20-25°C from 4.7 to 5.6% in coverage. The 15-20°C temperature indicated a decrease from 81.5 to 78.9% in coverage in this mountain range (Figure 6). In the Karakoram range, the <250 mm rainfall indicated a decrease from 71 to 37.1% in coverage, while the rainfall range 500-700 mm exhibited an increase from 0.6 to 1.9% and 250-500 mm from 28.5 to 61% in coverage (Figure 5). Tahir et al. [49] and Latif et al. [50] reported an increase in winter precipitation in this region. An increasing trend in the mean annual area-weighted temperature was observed in the Gilgit-Baltistan region of UIB during the 1901-2014 period [47]. The temperature range 10-15°C exhibited an increase from 64.6 to 66% in coverage, while 15-20°C indicated a decrease from 35.4 to 34% in coverage in this mountain range. In the Himalaya range, the mean annual rainfall showed an increase from 737 to 798 mm in this range. The coverage of 500-700 mm rainfall exhibited an increase from 4.9 to 14% and 750-1000 mm from 2.6 to 16.1% (Figure 5). The 10-15°C temperature exhibited a major positive change, i.e., from 41.4 to 60.5% in coverage in this mountain range during the 1960-2019 period. The summer temperatures have increased in the sub-mountainous region, while somewhat decreased in the high mountainous zone [51]. Overall, the 500-750 mm rainfall range indicated an increase in coverage from 9.3 to 13.6% and 250-500 mm range from 27.2 to 38.8% in the HKH region (Figure 5). According to Hewitt [9] and Fowler and Archer [48], an increasing winter precipitation and a minor declining trend in summer temperature have been observed in this region. The temperature range 10-15°C exhibited an increase from 41.8 to 48.2% in coverage, while other temperature ranges indicated a minor decrease in coverage in the HKH region during the 1960-2019 period (Figure 6). Owing to rising temperatures and precipitation, and lack of tree cover, floods have become more frequent and intense in Pakistan since 2010 [52]. According to Shrestha et al. [7], the summer temperatures in the Indus Basin could rise by 2 to 5°C under low emission scenarios by 2050, and even more in the HKH region under high emission scenarios. Additionally, under both low and high emission scenarios, winter temperatures are expected to rise by 2 to 4°C throughout the basin by 2050. In the wake of growing warm temperatures, more frequent GLOFs and subsequent damages are expected in the region in the future [53, 54].

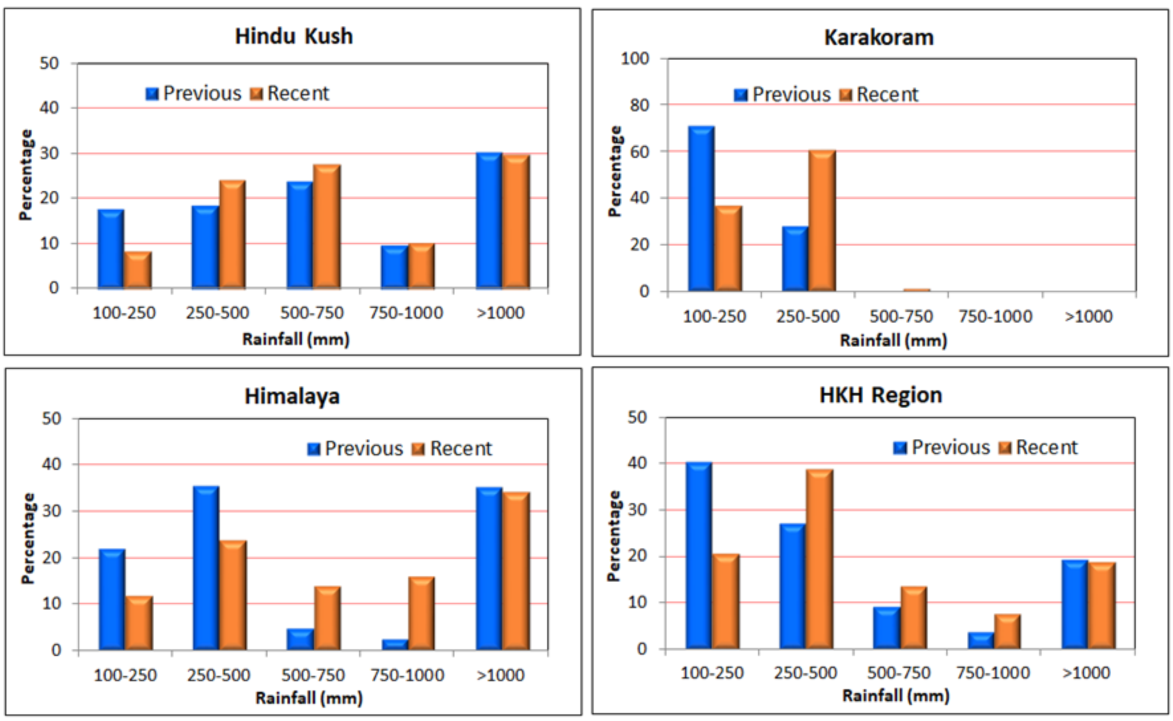

Figure 5. Percentage coverage of annual rainfall during 1960-1989 and 1990-2019 normals in the HKH region.

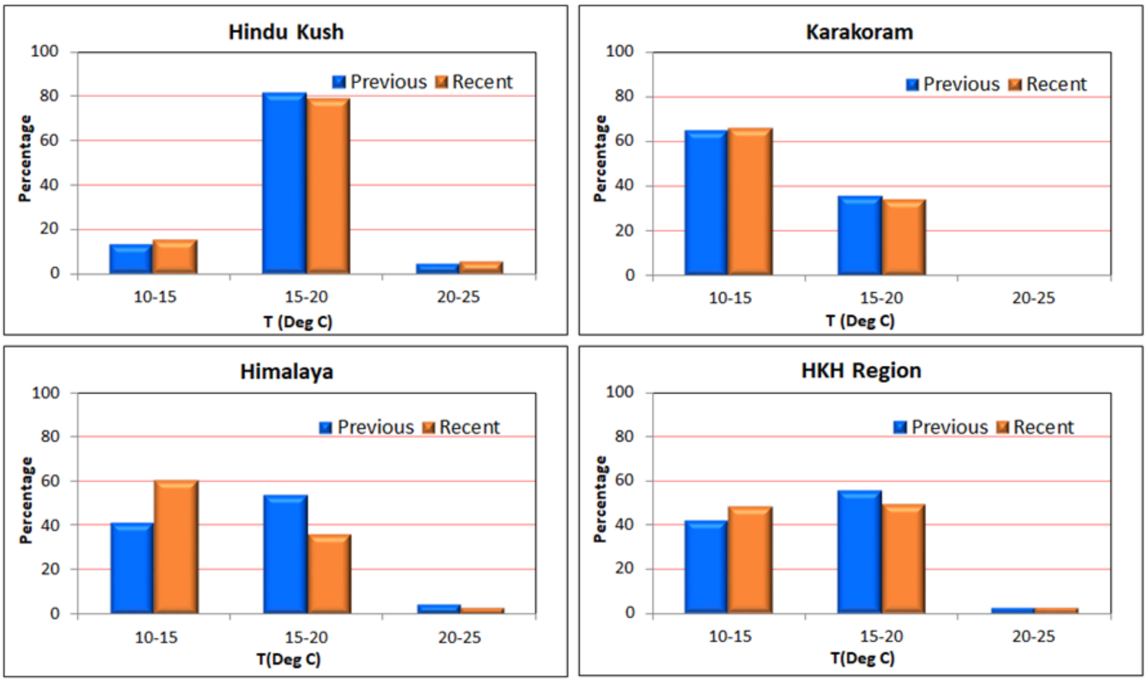

Figure 6. Percentage coverage of mean temperature during 1960-1989 and 1990-2019 climatic normals in the region.

3.2 GLOF risk analysis

The changes in climate parameters (i.e., temperature and precipitation) have a direct and indirect relationship with lake dynamics and formation. In several cases, a direct relationship appears to exist between lake growth and precipitation, as occasional heavy downpours like the one during 2010 and melting of glaciers under increased temperatures caused the expansion of many lakes in various parts of the UIB (personal communication). The formation of lakes due to the indirect impact of climate change may include damming of rivers by surging glaciers, landslides, rockfall, mud, and debris flows. Some examples are the formation of Khalti Lake in 1980, Darkut Lake in 1990, Sosat Lake in 1994, Chashi Lake in 1991, and Chartoi Gupis Lake in 2000. These lakes are fed by meltwater runoff generated from high ice-capped peaks and surrounding glaciers. Among the total 3,044 glacial lakes (area about 134.8 km^2 ±12.9%) identified in the UIB during 2013, 36 lakes were found susceptible to GLOF hazard [26]. About 41% of the total lakes were classified as glacier-fed lakes, mostly belonging to end-moraine dammed, cirque, and supraglacial types [17]. The expansion in lake area was observed to be dominant in the Karakoram and Himalaya ranges during the 2001-2013 period (Table 3). The majority of the glacier-fed lakes in the Gilgit, Hunza, and Shyok basins of the Karakoram, and Jhelum basin of the Himalaya indicated expansion in area. Overall, the number of lakes indicated an increase of about 26% in the three HKH ranges since 2001. The growth in the number and area of lakes in various regions may be attributed to changes in climate and cryosphere in recent decades [5, 20].

Table 3. Physical changes in glacial lakes in different HKH ranges of Pakistan during 2001-2013 period

Range	2001		2013		% Change	
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
Hindu Kush	711	38.26	722	33.36	1.5	-12.8
Karakoram	887	47.72	1325	57.99	49.4	21.5
Himalaya	822	40.38	997	43.47	21.3	7.7
Total	2420	126.36	3044	134.82	25.8	6.7

Numerous GLOFs with varying degrees of socio-economic impacts have been reported in the HKH region [17, 32, 55-62] (Table 4). On May 7, 2022, a lake developed by the surging of the Shisper glacier [63] breached suddenly due to an abrupt change in temperature and precipitation, resulting in a massive discharge of water mixed with debris in the upper Hunza valley (Figure 7a). The GLOF event resulted in damage to a main bridge, the Karakoram highway, two micro hydro-power stations, 52 houses, numerous trees, and agricultural land downstream in the Hassanabad village [61]. A number of GLOF events took place in the Upper Hunza valley between 2008 and 2017 due to the filling and breaching of supraglacial lakes over the Ghulkin glacier. These events caused damage to downstream road infrastructure, settlements, agricultural land, and irrigation channels (Figure 7b). As a result of damage to water channels, water shortages occurred, seriously affecting agriculture production and the livelihoods of the communities. During 2005 and 2012, Sosot village in Ghizar district was hit by GLOFs that caused heavy damage to cropland, property, and infrastructure (road and power houses) downstream [60]. A part of the village and a 3 km road section were destroyed by intense floods accompanied by heavy boulders and sediments (Figure 7c), which ultimately blocked the Gilgit river temporarily in the valley. A GLOF on the Unna glacier in 2010 produced a significant flood in Boipher Nallah, destroying the natural forest and the villages of Sat, Dart, Ghossonar, Chira, and Bulchi in the Bagrot valley [58]. Furthermore, GLOFs during 2012 and 2013 in this valley caused the death of more than 30 cows and numerous sheep/goats, and damaged one school, 2 bridges, 7 irrigation channels, dozens of fruit trees, and half a kilometer of the main tract containing footbridges.

Table 4. Major flash flood/GLOF events occurred at various locations of the study area

Year	Damages/Losses
1890	Diran glacier burst caused loss of human, livestock, wildlife damage to natural forest, rich agricultural lands and houses of the Biabari, Koshali Het in Sat area.
1905	Dubani glacier burst caused a huge damage to natural forest as well as the settlements of Taisote and Massingot villages.
1909	GLOFs in Ghotomi, Dodi Rung Bari Bar site of the Dubani Peak resulted in heavy damage to natural forests and human settlements in Sat, Ghosonar and Darija villages.
1951	Kotor glacier burst caused a huge damage to forest, fruit trees and settlements in various villages.
1972	Unna glacial lake burst caused heavy flood in Boipher damaging natural forest and the settlements of Sat, Dar, Ghosonar, Chira and Bulchi villages.
1974	Dubani glacier burst caused heavy damage to natural forest as well as the settlements.
1978	Hinarchi glacier burst resulting complete damage occurred to natural forest and agricultural land of Bulchi and Chira villages.
1982 & 1985	Una glacial burst causing heavy flood in Boipher nallah caused damages to natural forest and the settlements of Sat, Dart, Ghosonar, Chira and Bulchi villages.
1992	Hinarchi glacier burst resulting complete damage village Khama, natural forest and agricultural land of villages Bulchi and Chira. Dubani glacier burst. A huge damage occurred to natural forest as well as the settlements in the downstream.
1997	Dubani glacier/lakes burst caused huge damage to natural forest as well as the settlements of Taisote and Massingot villages. Loss of a human life and 60 goats was also reported.
1998	GLOF caused loss of 7 cows, 25 sheep and goat, and damaged about 100 fruit trees in Gilgit.
2007	Rakaposhi glacier/lake burst resulted in damage to natural forest of Malipai and Khama villages. GLOF occurred on Passu glacier in Upper Hunza valley.
2008	GLOFs and heavy rains damaged 8 houses in Bulchi, the Imambargah, Mosque, a school and about 500 knals of land. In Farfoo, the flood damaged about 400 knal land with crops (wheat and potato), 8 cattle sheds and in Chirah, about 200 knal land with crops. GLOFs occurred on Ghulkin glacier in Upper Hunza valley.
2009	Hinarchi glacier burst resulting complete damage to natural forest, 30 knals cropland in Bulchi and 40 knals in Chirah village.
2010	Unna glacial lake burst caused heavy flood in Boipher nallah and damage to natural forest and the settlements of Sat, Dart, Ghossonar, Chira and Bulchi villages. Dubani Glacier burst resulted in huge damage to natural forest as well as the settlements of Taisote and Massingot villages.
2012	GLOF damaged one school, 2 bridges, 7 irrigation channels, 8 cows, about 50 knals of private land with crops, cattle sheds and washed out a half km of the main tract and footbridges.
2013	GLOF caused death of 33 cattle, 108 sheep, 29 goats, and loss of 57 fruit trees in the Gilgit region.
2015-2017	GLOF events occurred owing to fill and breach of the supraglacial lakes in Upper Hunza valley.
2022	Breaching of a lake caused destruction of infrastructure, property and agricultural land in Hunza valley.

Figure 7. A massive GLOF caused destruction of valuable property and infrastructure in the upper Hunza valley (surveyed in 2022) (a); Intense GLOFs caused damage of nearby settlements and cultivated land in the Hunza (b) and Gilgit river basin (c), Farm forestry in the floodplains (d) and Seabuckthorn plantation over mountain slopes provide multiple benefits including resilience against sudden floods and slope instability (e), and locals have planted fruit trees along a flooding route passing within their village to improve their livelihood as well as create protection against occasional floods (Ghanche district, surveyed in 2022) (f).

3.3 Flood risk management

There is a need to adopt measures to address social, economic, and environmental issues related to the impacts of climate change for sustainable flood risk mitigation in this region [64]. Several sustainable development goals (SDGs) pertaining to water management, climate change, resilient infrastructure, sustainable cities and communities, and sustainable use of terrestrial ecosystems are indirectly touched upon by the issue of flood risk management [65]. In contrast with conventional or grey infrastructure techniques, nature-based solutions (NBS) possess multifunctional characteristics that have the ability to conserve natural capital and increase the overall connectivity and resilience of the landscapes [66]. Several structural measures are applied for reducing possible peak surge discharge from a GLOF lake, i.e., construction of an outlet control structure, controlled breaching, pumping or siphoning out the water from the lake, and making a tunnel through the moraine, which require large funding, technical expertise, and ongoing maintenance [67]. Although such measures tend to be more effective in the short term in providing immediate protection against GLOF events, the implementation of such measures requires specialized equipment, materials, and techniques, which can be financially unsustainable, particularly for low-income regions [68, 69]. The ecosystem-based means, while potentially less effective immediately, provide more sustainable long-term resilience.

3.3.1 Ecosystem-based land use planning

It is the process of recommending appropriate communities of potential land uses based on ecosystem capabilities. Proper planning and management of the mountain ecosystem is important to provide protection against common natural hazards like floods, landslides, droughts and storm surges. Provision of ecosystem sustainability and benefits (Table 5) should be ensured in integrated land use planning [70-72] to help improve livelihoods and develop resilience against economic shocks during any flash flood event.

Table 5. Potential land use for livelihood improvement and sustainable development

Potential land use	Suitability
Farm forestry and fruit tree plantation	Farm trees and fruit orchards can control land degradation and flood risk, besides providing timber, fresh/dry fruits and other non-wood products (Figure 7d).
Seabuckthorn plantation	The native wild plant like seabuckthorn should be conserved and promoted to stabilize slopes near floodplains and roads (Figure 7e). Its fruit pulp and oil are highly nutritious which has high marketing value.
Olive plantation	Large area is highly suitable for olive cultivation for its high production and oil recovery.
Clean fruit and vegetable nurseries	These is need to establish clean fruit and vegetable nurseries (Apricot, cherries, walnut, apple, almond, potatoes) for hybrids and certified seed production.
Livestock farming	There exists high potential for establishing livestock farming (cattle, yaks, buffaloes) especially for diary purpose.

Improper planning and mitigation measures could cause GLOFs to be more destructive in the future. The balance between social, environmental, and economic values is important for flood management—it may include allocating land to various uses over a landscape [73, 74]. Owing to recent natural disasters and water shortages, public expectations on the role of forests (which aid in the prevention of disasters and provide ecosystem services like food, fuel, and good quality water) have increased. Land use planning must be intended to secure all the beneficial aspects of the communities as well as the ecosystem. During any GLOF event, mostly agricultural land, irrigation channels, road infrastructure linking trade and tourism, and consequently the livelihoods of the communities are at risk [75-77]. When irrigation channels are damaged, the water supply is sometimes shut off for months, resulting in a shortage of water for the communities' survival. Land use planning should focus on clear demarcation of vulnerable areas, floodplain reconnection, and in some places increasing the size of the floodplains to provide enough space for conveying a heavy amount of floodwater [78]. Any development plan must take into account a safe distance from hazard-prone areas (river banks, floodplains, and landslides) [79], and allocate safe places for establishing temporary shelters, storage of food grains, and other necessities for flood relief purposes. The glacial ecosystem, including glaciers, lakes, and their floodplains, should be declared protected to restrict unlawful human interruptions in the system.

3.3.2 Sustaining ecosystem health

Improving ecosystem health is important for reducing the risk of flood disasters, creating economic opportunities, and improving the livelihoods of vulnerable communities. A well-managed ecosystem increases communities' resilience in three ways: i) lowering their exposure to direct flooding, ii) giving them the ability to control their immediate surroundings, and iii) improving their ability to respond to climatic shocks [80, 81]. Launching afforestation/reforestation programs in the region would help absorb flood hazard shocks and reduce negative impacts in the future. Preserving the forest environment and pastures at higher elevations would aid in lowering the risk of overland water flows, flash floods, and sediment loads downstream [82]. Furthermore, site-specific resource conservation techniques and environmentally friendly measures may be implemented to restore ecosystem health on a sustainable basis. Healthy ecosystems recover more quickly and are more resilient to the effects of extreme events and possible risks than degraded ecosystems [83]. The degradation of forests may cause a rise in warm temperatures, which would ultimately affect the glacial environment of the region [60, 84]. Restoring ecosystem health would increase the resilience of local communities and, conversely, reduce their vulnerability to flood hazards [85]. During floods, affected communities habitually turn to their adjacent environment for sustenance (food, fuel, water, and shelter). Thus, protection of ecosystem resources needs to be ensured as they provide important goods like food, fiber, medications, and construction material significant for establishing human safety and flexibility against disasters [86]. This will also provide opportunities for diversification, resilience against future multiple hazards, and sustainable economic development in the region. Ecological restoration of degraded areas would be helpful for sustainable growth in this region. In Chitral, severe degradation of the forests was happening a decade ago, but after imposing a ban on cutting green trees by local communities, the forest ecosystem has improved [60]. According to WWF [87], a total of 0.25 million plants of multipurpose tree species were grown in seventeen vulnerable valleys of the Gilgit and Astore basins. The communities are responsible for looking after the plants, such as irrigation and replacement of dried/damaged plants with new ones during the post-planting phase. Plantation of food forests - multifunctional agroforestry systems has potential in this region as the climate here favors the growing of fruit trees and horticultural crops, and more than half of the population is food insecure in this region [88]. In addition to preserving moisture in the fields, agroforestry and intercropping fruit trees with other crops can help reduce erosion by mulching the soil, which may help disperse the kinetic energy of raindrops and improve soil structure [82]. The community-based conservation programs, such as social forestry, plantation of seabuckthorn forests, production of off-season vegetation, climate-resilient and high-value seeds, can help improve ecosystem health and provide socioeconomic benefits. The seabuckthorn plantation in the uplands helps stabilize mountain slopes (Figure 7e), and the plantation of woody/fruit trees along the floodplain may reduce the risk of flood hazards downstream (Figure 7f). The programs for mountain ecosystem development can be sustained through the involvement of communities in the planning process, which would provide economic and livelihood opportunities in the long run in the future.

3.3.3 Strengthening response capacity

The increase in frequency and magnitude of GLOF incidences in recent decades demands an adequate response capacity from vulnerable communities to cope with future flood hazards. Capacity building of local communities and institutions through knowledge and resource sharing, and skills transfer is essential for effective flood risk mitigation in vulnerable areas [17]. Mock drill events should be organized for volunteers at the village level, including school teachers, guards, dispensers, and drivers, so that communities can prepare themselves for GLOF risk reduction. Involvement of different stakeholders in decision-making and continuity of support (technical and financial) are important to achieve sustainability in the risk management process. Indigenous institutions in various villages are playing a proactive role in disaster risk management (DRM) and conservation of common property resources, such as forests, pastures, glaciers, irrigation channels, roads, and other resources of common interest. For example, community-based organizations (CBOs) are involved in planting fast-growing tree species, such as Russian olive, poplar, and alfalfa, on communal lands in various parts of the region [87]. The Aga Khan Rural Support Programme (AKRSP) has formed village and women organizations (V&WOs) in each village to undertake development activities and manage village affairs, including disaster risk reduction. The Village Disaster Management Groups and Panchayat committees are mainly oriented towards preparedness, rescue, and relief activities. Villagers typically assist impacted families in leaving flood-prone regions during flood events by working on a self-help basis [17]. However, gaps exist in coordination and the capacity of local communities to manage the risk of natural hazards like GLOFs, landslides, and debris flow. The communities' action committees should be responsible for communicating with the government or donor organizations, sharing early warnings and other useful information, stocking relief supplies, and facilitating wider-scale planning in the area [67]. The Gilgit-Baltistan Disaster Management Authority (GBDMA) is involved in sharing knowledge and mobilizing resources available from the government and non-governmental organizations. It would be beneficial to focus on the locals' ability to observe their local surroundings; for example, locals can detect clues of glacial hazards by carefully watching abnormal events in the glaciers, such as unusual sounds from the glacier, sudden drying of glacial streams for 2-3 days due to englacial blockage of water conduits with ice or debris, heavy accumulation or rise of water in proglacial lakes, and sudden increases in the lakes' outflow [60].

Typically, women who have limited capacity and access to essential resources are more susceptible to flood hazards as men are mostly engaged in laboring out of the villages [89]. In such cases, low-income women should be provided with remittances or soft loans and trained in disaster risk reduction to make them able to respond efficiently during any flood hazard [90]. A disaster risk fund may be established for preparedness, rapid response, and relief. The relief agencies need to be adequately equipped with distribution supplies like tents, blankets, food items, and necessary household items. The role of the public sector is important in a massive relief operation, releasing needful information and alerts, introducing high-yielding seeds/planting material, land use planning, and shaping regulations [91]. The provincial agriculture departments, Mountain Agricultural Research Centre of Pakistan Agricultural Research Council, and universities which have training facilities in major towns and cities [72] can be engaged for enhancing the proficiency of the communities in promoting healthy ecosystems and nature-based flood risk management in the region. Along with the NBS approach, it would also be beneficial to focus on understanding hydrodynamic processes of floods, new methodologies, and enhanced capacities of current approaches to improve infrastructure for flood risk management [65]. Integration of traditional and scientific knowledge, awareness, and education would be supportive for effective risk management in this region [92].

4. Conclusion

In the present study, climate dynamics, GLOF risks, and nature-based risk management strategies were evaluated for sustainable development in the HKH region of Pakistan. The climate analysis indicated an increase of 2.4% in mean annual rainfall in the Hindu Kush, 33.8% in the Karakoram, and 8.3% in the Himalaya range during the 1960-2019 period. As a result of changing climate, the majority of the glacier-fed lakes indicated an expansion in lake area in the Karakoram and Himalaya ranges. Climate change had influenced the cryosphere regime, resulting in the frequent occurrence of flash floods/GLOF events leading to environmental degradation, loss of infrastructure, property, and valuable lives downstream. Unplanned development of settlements, especially near active glaciers and lakes, is highly risky and could result in the loss of valuable property and lives during any outburst event.

Effective nature-based flood risk management needs to be promoted by preserving the natural ecosystem, enhancing its health, and strengthening the response capacity of vulnerable communities in the region. Vulnerability of habitations and agricultural land to intense glacial flooding can be reduced through ecosystem-based land use planning. There should be a clear demarcation of vulnerable areas, and the focus must be on reconnecting floodplains and occasionally enlarging floodplains to provide adequate room for transporting large volumes of floodwater to reduce flood risk downstream. Launching afforestation and reforestation projects might help absorb shocks from flood hazards, reduce flood runoff, sediment loads, and socio-economic susceptibility. Site-specific resource conservation techniques and environmentally friendly measures may be adopted to restore ecosystem health on a sustainable basis. Capacity building of local communities and institutions through resource sharing, skills transfer, and enhanced knowledge dissemination is crucial to improve flood risk mitigation in vulnerable areas. It is essential to promote good practices of NBS in flood risk management through raising awareness, demonstration, and initiating educational programs. Local experts and institutions must be included in the development of risk management plans at the policy level for GLOF risk management to be effective. Long-term research on climate change and glacio-hydroglacial assessment would be supportive in effective early warning and risk mitigation of flash flood hazards in this region in the future.

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