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Research Article

Spatio-Temporal Monitoring and Risk Mapping of Glacial Lake Outburst Flood in Hunza Valley, Pakistan

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Abstract: Glacial lake outburst flood (GLOF) disasters are serious and potentially increase huge risks to livelihoods and infrastructure in the mountain regions of the world. The northern highland regions of Pakistan are home to some of the biggest alpine glaciers. In this investigation, the Hunza Valley of Pakistan has undergone remote sensing-based risk assessment for Glacial Lake Outburst Floods. Borith and Passu Lakes were chosen to identify flood risk in the downstream areas. Landsat images were used from 1990-2020. Different spectral indices such as the Normalized Difference Snow Index (NDSI), Normalized Difference Glacier Index (NDGI) and Normalized Difference Water Index (NDWI) were applied to evaluate snow cover changes. Furthermore, these Lakes were digitized to evaluate any variation in Lake Areas, over the study period. Also, built-up areas close to lakes were digitized to identify total risk. The Land Surface Temperature (LST), NDSI, NDGI, NDWI, Digital Elevation Model (DEM) and Slope variables were given weights using the Analytic Hierarchy Process (AHP) method. In the analysis of flood risk mapping, maximum weight was assigned to Land Surface Temperature, and minimum weight was assigned to the slope. The result revealed that the settlements located in the Ghulkin, Gulmit, Husseini, Passu, Zarabad, and Khorramabad are at moderate risk while settlements located near Hunza River such as Karimabad, Khanna Abad, and Aliabad are at high risk. The outcome also showed that Borith Lake's area expanded, going from 0.059 km^2 in 1985 to 0.074 km^2 in 2020 and Passu Lake's area also grew, going from 0.074 km^2 in 2005 to 0.077 km^2 in 2020. In last, Buffer analysis was performed to identify areas that are likely to be affected by the flood. The result of the study can help carry out a downstream risk assessment and better preparedness for future flood hazards.

Keywords: Glacial Lake, Climate Change, Outburst Flood, Risk Mapping, Analytic Hierarchy Process, Hunza Valley.

1. INTRODUCTION

Glaciers are retreating and increasing the occurrence of glacier-related hazards. Since 1880, the world's temperature has risen by 0.85 °C [1]. The average temperature in the Indian Sub-continent can be increased by 3.5-5.5 °C by 2100 [2]. Glacier meltwater increases the river discharge but in the longer term, it reduces it [3]. The Indus irrigation system is an important part of Pakistan's economy [4], and the main source of the Indus River is glacial meltwater [5]. The world's largest glaciers can be found in Pakistan's northern mountain ranges, the Karakorum, Himalaya, and Hindu-Kush [1]. Siachen is the longest glacier outside the Polar Regions, about 75 km long located in the Karakorum Mountains. Hispar Glacier is 61 km in length [6]. Karakorum glaciers are highly influenced by the Indian monsoon. The glaciers of Karakorum have steep hill slopes and mostly are

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debris-covered [3]. Mostly precipitation occurs in spring and winter in the form of snow on the glaciers of Karakorum because they are at extremely high altitudes. The climate of Karakorum is altered by Tibetan anticyclones and westerlies which increase snowfall in winter [7]. The average annual precipitation in Baltoro Glacier is 2500 mm at 8000 m. The highest precipitation occurs in the summer monsoon in the Hunza basin [8]. Global warming caused a mass loss of 10% in high mountains of Asia which increased by almost 3% sea level [9].

Glacier advance and retreat are caused by climate change and monsoon rains raise the possibility of a lake bursting [10]. The Karakorum, Himalaya and Hindukush (HKH) region is also influenced by climate change and GLOFs came out as a looming threat in this region. Glacier area variations are a serious menace in the Karakorum region [11]. Natural disasters like the Glacial Lake Outburst Flood (GLOF) can become more severe due to climate change, endangering the population [10]. The impact of a GLOF event downstream is quite extensive in terms of damage to roads, bridges, trekking trials, villages, and agricultural lands as well as the loss of human life and other infrastructure [12]. When a glacier melts, glacial lakes typically form at the snout of the glacier. HKH is the most affected region of GLOF. Critical glacial lakes can destroy the CPEC route along the Karakorum Highway [13]. More attention is required to monitor extension in lakes created by debris-covered glaciers because of their potential burst. The glacial hazard of GLOFs can destroy the farmlands and downstream settlements [14]. Increased sea levels, flooding, erosion, and frequent GLOFs are the results of this. There is a significant spatial variation in the stable, advancing, and retreating glaciers found in the Karakoram region [15].

The glaciers of Karakorum have been retreating since 1990 but surging in glaciers has also been noticed. Climate is the most important factor of change in the glacial behaviour of Karakorum [16]. Some glaciers of Karakorum are surging such as Hassan Abad Glacier [06]. In the last 15 years, Passu Glacier has undergone a forceful retreat and increased danger in Atta Bad Lake which can burst soon [17]. Passu glacial lake experienced two outbursts in two decades destroying houses and a bridge on Karakorum Highway, debris flowed downstream consuming the structures on the way [18]. To study outbursts, there is a need to identify critical lakes to promote preventive measures [19]. In 1980, the International Karakoram Project conducted a survey along the Karakoram Highway in the Hunza Valley and identified 339 catastrophic incidents [10]. A glacial decline in Karakorum resulted in glacial lakes which have a high risk of GLOF.

Hassan Abad Hunza experienced five GLOF events by the surging of Shishper Glacier and the most recent was recorded in May 2020 [13]. When the water of the Ghizer River was obstructed and burst after a few months, it led to the creation of Khalti Lake in 1999, which caused a significant loss in villages downstream. Between 2007 and 2009, two GLOF episodes from the Ghulkin Glacier were documented, both of which shut down the Karakorum Highway [20]. In Huaraz (Peru) 4500 people died in 1941 of the GLOF event [21]. Two GLOF events occurred in Gupis Valley in 1994 and 1999 causing a huge loss of land and infrastructure [20]. Hunza River Basin has a previous record of severe flooding [22]. Land located in Gulmit is used as agricultural land and the maximum glacial retreat is recorded during ablation season. The glacier area of Gulmit (in Hunza Nagar) is about 11-kilometre squares [2]. The glaciers Ghulkin and Gulmit are situated south of Batura Glacier, both are debris-covered and the primary source of water to the Hunza Nagar district and Hunza River. Glacial lakes are formed by the meltwater of glaciers.

The volume of water in lakes increases due to an increase in glacier melting, and lakes that abruptly burst might damage towns downstream. This event is referred to as the Glacial Lake Outburst Flood (GLOF). In the past few years, many glacial lakes have developed in Pakistan's HKH region. Gilgit Baltistan has experienced many GLOF events. GLOF can take the lives of humans and livestock and cause damage to roads, bridges, and farms land. However, global warming has had a substantial impact on Pakistan's glaciers [23]. The first decade of the twenty-first century is regarded as the planet's hottest decade. Lake located at the terminus of Passu Glacier had records of outbursts in the last two decades causing a huge loss to the downstream settlements in Hunza [22]. Five GLOF events occurred in Hunza Basin between 2007-2008 and posed a severe threat to near settlements of the Karakorum Mountain Range [4]. According to Amin *et al*. [20], Sosot village experienced a GLOF event in 1994 and two GLOF events were recorded from Ghulkin Glacier. In the past 200 years, the Karakorum Range has seen 35 outburst episodes. Due to the lack of mitigation, management, and government policies, a huge loss of land and infrastructure and because of poor livelihood, people are not able to respond quickly and effectively to any flood situation [13]. Therefore, there's a need to constantly monitor the glacial lakes and the factors affecting them. The study's primary goal is to locate regions that may be at risk of GLOF flooding downstream.

2. MATERIALS AND METHODS

2.1. Study Area

The study area includes Gilgit Baltistan, as well as Hunza Nagar District and Upper Hunza, a sizable, glaciated region in North Pakistan. The Hunza lies between 36.3167° N and 74.6500° E at an elevation of 2,438 meters. The Hunza Valley contains the Passu and Borith lakes that have been selected. These lakes were chosen to identify potential risk for the study areas as shown in Figure 1. The elevation of Borith Lake is 2600 meters above sea level. It lies about 2 km to the north of Gulmit. A sizable body of water known as a lake is located beneath the settlement of Hussaini. South of the tongue of the Batura Glacier, close to the Passu Glacier, there is a lake called Passu Lake.

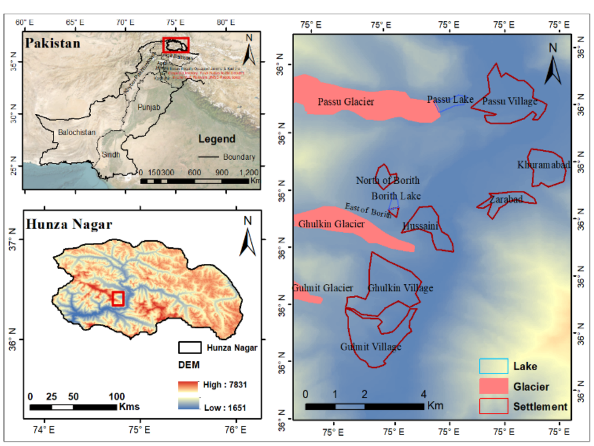

Fig. 1. Location of the study area.

2.2. Data and Its Sources

For this investigation, the Digital Elevation Model (DEM) and multi-temporal Landsat datasets were utilized. Since Landsat satellites have provided data since 1972, therefore various Landsat series datasets were used. For this investigation, the cloud-free Landsat images for April, September, and December were gathered. Landsat (TM/ETM+/OLI) images in total 12 were obtained from the US Geological Survey (USGS) as illustrated in Table 1. The Study area has been covered in total four Landsat satellite tiles with paths and rows 149-34, 149-35, 150-34, and 150-35. In specific, Landsat images for the years 1993, 2001, 2010 and 2020 were acquired for comprehensive analysis.

2.3. Data Analysis

The spatial overlay technique was applied to the resulting layers of Normalized Difference Water Index (NDWI), Normalized Difference Glacier Index (NDGI), Normalized Difference Snow Index (NDSI), Land Surface (LST), and slope and flow accumulation (Table 2 and Figure 2). Based on this analysis, the risk areas were calculated for settlements around these selected lakes and surrounding glaciers.

For risk area identification, different indicators were studied and while performing weighted overlay analysis different weights were assigned to variables by using the Analytical Hierarchy Process (AHP) technique [24]. Maximum weight was assigned to Land Surface Temperature which was about 38% because it is the driving force behind the glacial behaviour, snow cover and expansion rate of lakes.

Table 1. Details of used landsat data.

Satellite and sensors	Bands used	Spatial resolution (m)	Month	Year
Landsat 5-TM	2,3,4,5,6	30	Nov, Dec	1993
Landsat 7-ETM+	2,3,4,5,6	30	Nov	2001
Landsat 5-TM	2,3,4,5,6	30	Nov, Dec	2010
Landsat 8-OLI/TIRS	3,4,5,6,10	30	April	2020

Table 2. Source and utility of spectral indices used in the study.

Spectral indices	**Utility**
Normalized Difference Snow Index (NDSI)	Maps that show where there is snow and where there isn't [28]
Normalized Difference Glacier Index (NDGI)	Identifying and mapping the snow-ice and ice-mixed debris class [29]
Normalized Difference Water Index (NDWI)	Mapping surface water [30]

2.3.1. Calculation of TOA (Top of Atmospheric) spectral radiance

The thermal infrared band is converted to the Top of Atmospheric (TOA) spectral radiance through rescaling factors as mentioned in the metadata file of the Landsat satellite and measured through the equation below:

$$L_\lambda = \left(\frac{LMAX\lambda - LMIN\lambda}{QCALMAX - QCALMIN}\right) - (QCAL - QCALMIN) + LMIN\lambda$$

2.3.2. Land surface temperature (LST)

In the final step thermal infrared data can be obtained from spectral radiance to measure land surface temperature [25] to degree Celsius (°C) by utilizing the equation given below:

$$LST = (K2/(In(K1/L) + 1)) - 273.15$$

2.3.3. Normalized difference snow index (NDSI)

Snow is recognized using NDSI [26]. For mapping the snow extent, NDSI has been widely employed. The following formula was used for calculating NDSI.

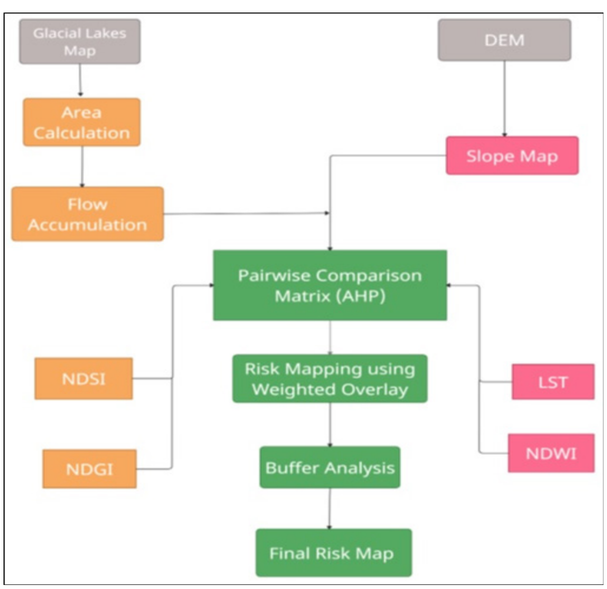

Fig. 2. Methodological framework.

$$NDSI = \frac{Green\ Band\ Reflectance - SWIR\ Band\ Reflectance}{Green\ Band\ Reflectance + SWIR\ Band\ Reflectance}$$

For Landsat 5 & 7: $NDSI = \frac{B2-B5}{B2+B5}$

For Landsat 8: $NDSI = \frac{B3-B6}{B3+B6}$

2.3.4. Normalized difference water index (NDWI)

NDWI is a method that was created primarily to designate open water features, improving their visibility while removing soil and vegetation elements [27]. The following formula is applied for calculating NDWI.

$$NDWI = \frac{Green-NIR}{Green+NIR}$$

Where NIR is near-infrared band reflectance. The same formula was used with the different band number for Landsat 5, 7 and 8.

For Landsat 5-TM: $NDWI = \frac{b2-b4}{b2+b4}$

For Landsat 7-ETM+: $NDWI = \frac{b4-b5}{b4+b5}$

For Landsat 8 (OLI): $NDWI = \frac{b3-b5}{b3+b5}$

2.3.5. Normalized difference glacier index (NDGI)

A numerical indicator called the NDGI uses the green and red spectral bands to assist find and track glacial ice. The primary remote sensing uses of NDGI are for the detection and monitoring of glaciers. The following formula was applied for calculating NDGI.

$$NDGI = \frac{Green\ band - Red\ band}{Green\ band + Red\ band}$$

For landsat 5 & 7: $NDGI = \frac{b2-b3}{b2+b3}$

For landsat 8 (OLI): $NDGI = \frac{b3-b4}{b3+b4}$

2.4. Analytical Hierarchy Process (AHP)

When one or more alternatives are compared to one or more pertinent criteria, a decision is made. The criteria is weighed according to their relative value to prioritize some of these criteria above others. To manage complex choice issue constellations, risk management and decision guidelines have been developed and put into use recently. These guidelines place a strong emphasis on risk communication and stakeholder involvement. One of the most effective and well-known methods for evaluating weight is the analytical hierarchy process (AHP), which was developed by Saaty [24]. Several natural hazard studies have employed the AHP approach, which estimates the eigenvalues of the components matrix and enables the evaluation of the judgments' consistency [31]. It has already been described as one of the most promising strategies for weight improvement.

In this study, through a review of the literature, some variables affecting GLOF events as referred to in Table 3, were shortlisted. These variables encompassed the glacial ice, snow cover, debris cover and climatic domains. These variables were assigned weights according to the pairwise comparison matrix suggested by Saaty [24]. Weights were assigned to gauge the impact of these variables on GLOF events by using the AHP technique. The AHP uses math and psychology to organize and analyze complicated decisions. It helps in assigning weights to indicators [12]. The weights for this study were finalized after taking expert guidance from field experts i.e. Pakistan Meteorological Department (PMD) and the Surface Water Hydrology Project (SWHP). Maximum weight was given to LST almost 38% and the minimum weight was given to slope almost 6% depending upon the variable which triggers most of the GLOF event.

3. RESULTS AND DISCUSSION

GLOF risk identification involves early and continuous identification of flood events that if they occur will have severe impacts on physical infrastructure and human settlements. For risk area identification different analyses were performed to identify at-risk settlements in the study area, also considering site factors such as climate.

3.1. Expansion in Area of Lakes

The lake's rate of growth is crucial since it raises the amount and severity of flooding that could occur. Using Google Earth (GE) images, lake boundaries were digitally recorded over two years. Figure 3 shows the boundary of Borith and Passu Lake in two different years. The change in the boundary of lakes can be easily detected. The result shows that the Borith Lake area has increased from 1985 to 2020 and the Passu Lake has also increased from 2005 to 2020. The Passu Lake was identified as high potential GLOF by the Pakistan Meteorological Department in 2015. It is because the melting of glaciers brought on by the recent increase in global temperatures led to the expansion of lakes [32].

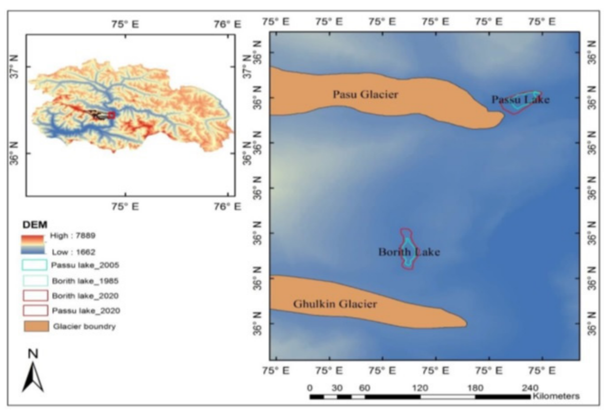

Fig. 3. Expansion in area of lakes.

Table 3. Pairwise comparison matrix of GLOF variables.

Indicators	LST	NDSI	NDGI	NDWI	Slope	SUM	n^{th} root	Priority vector (PV)	%
LST	1.00	2.00	3.00	4.00	5.00	15.00	0.68	0.39	38.76
NDSI	0.50	1.00	2.00	3.00	4.00	10.50	0.48	0.27	27.13
NDGI	0.33	0.50	1.00	2.00	3.00	6.83	0.31	0.18	17.66
NDWI	0.25	0.33	0.50	1.00	2.00	4.08	0.19	0.11	10.55
Slope	0.20	0.25	0.33	0.50	1.00	2.28	0.10	0.06	5.90
Sum	2.28	4.08	6.83	10.50	15.00	38.70	1.76	1.00	100
Sum PV	0.885	1.108	1.207	1.108	0.885	5.192	0.24	0.13	

Figure 4 shows the graphical representation of lake area changes. In 2005 the area of Passu Lake was 0.0742 sq km which increased in 2020 and is about 0.0778 sq km. The same is true for Borith Lake, whose area expanded from 0.0595 sq km in 1985 to 0.0742 sq km in 2020.

3.2. Flow Accumulation

Figure 5 shows the high value of flow accumulation across the selected lakes of Hunza Valley. Furthermore, the result shows that some tributaries of the Hunza River are passing through some villages namely, Hussaini, Ghulkin, Gulmit and Passu. As a result, these villages are at high risk if any GLOF flood occurs.

3.3. GLOF Risk Mapping

Figure 6 shows the risk mapping applied to identify the potential of GLOF flood risks in the selected study area, the weighted overlay analysis was performed to extract the risk areas. The result shows that almost all the settlements across selected villages are in the moderate risk zone. But the settlements along the river Hunza valleys are at high risk.

3.4. Buffer Zone Identification

To identify risk zones around glaciers, a buffer of 10 km was applied around the Passu, Ghulkin and Gulmit glaciers. Khadka *et al.* [12] used the same

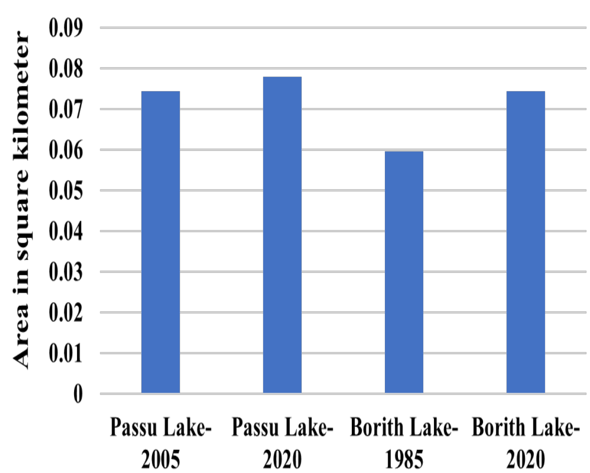

Fig. 4. Increase in area of lakes.

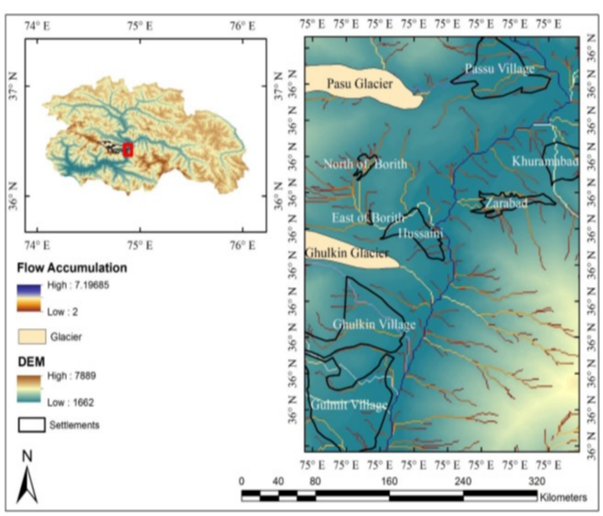

Fig. 5. Flow accumulation of Hunza.

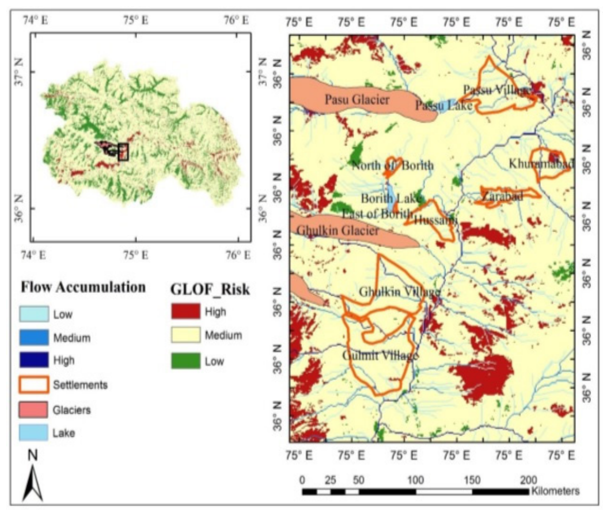

Fig. 6. GLOF risk map of Hunza.

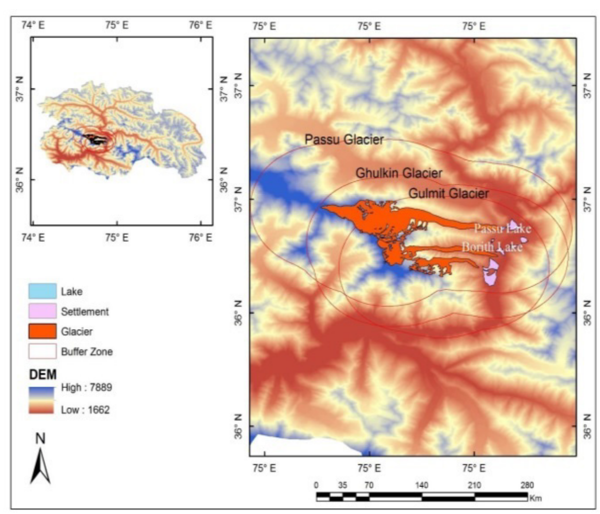

Fig. 7. Buffer zone identification.

distance to identify zones around glaciers in the Mahalangur Himalaya region. Figure 7 shows that the selected lakes and settlements under the buffer zone have extreme flood vulnerability that can be very destructive if any GLOF occurs.

4. CONCLUSIONS

In the present study, GLOF risk was calculated using datasets from 1990-2020 in the selected lakes. Different weights were assigned to different variables to calculate risk. The Pakistan Meteorological Department (PMD) and Surface Water Hydrology Project (SWHP) were consulted as an expert in this regard to assist us in weighting the variables. AHP is essential in this study as it allows for systematic weighting of various risk factors, leading to a more precise and informed GLOF risk evaluation and has been used in similar research [12, 31]. LST was given the most weight because it is the primary factor contributing to the rise in temperature. The study concludes that the settlements along river valleys are at high risk and settlements away from the river are at low risk. The Areas of selected lakes also increased over the past decade. The outcome also showed that Borith Lake's area expanded, going from 0.059 km^2 in 1985 to 0.074 km^2 in 2020. Passu Lake's area also grew, going from 0.074 km^2 in 2005 to 0.077 km^2 in 2020. Further studies have revealed that the volume and area of glacial lakes particularly Borith and Passu are shown to be increasing signalling a growing risk of GLOF events [33-35]. This increase in areas has the potential to be a significant threat to the GLOF and the settlements and other properties around selected lakes. The extremely vulnerable locations are found close to lakes and rivers, such as some communities along the Hunza River downstream of Passu Lake. The likelihood of Passu Lake bursting is low due to its natural drainage, but the projected losses in the event of GLOF are enormous. Hunza's Shimshal Valley has seen flooding from glacier lakes in the past. GLOF episodes have been documented in the Hunza valley, hence the glaciers of Hunza Nagar valley need to be watched for their lakes. 16000 people of Karimabad, 2005 people of Aliabad, 5000 people of Gulmit and people of surrounding settlements are at high risk if a GLOF event occurs. The study has taken LST, NDSI, NDGI, NDWI, and slope as the key parameters triggering the GLOF events in the major cryosphere areas, as the change in these variables due to climate changes, is making the region even more vulnerable. This study has provided a mechanism and application for the accurate risk mapping, damage assessment, and monitoring of glacier lakes and GLOFs. The results of this study will help build early warning systems in sensitive areas and reduce the negative effects of future GLOF events in the Hunza watershed. Future GLOF studies should investigate the long-term impacts of climate change on glacial lake dynamics and develop sustainable land-use practices to reduce vulnerability in high-risk areas.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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