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GLOF Hazard Assessment using Geospatial Techniques in Hunza Nagar, Gilgit Baltistan, Pakistan

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Abstract

Worldwide in different regions, increase in temperature has caused variations in many natural phenomena particularly expansion, contraction and creation of glacial lakes Hindu Kush Himalayas (HKH) region. In the recent past, several of these lakes have been burst out and generated Glacial Lake Outburst Floods (GLOFs) causing considerable human life loss damages to infrastructure and properties in downstream areas. This study is an effort to assess GLOF hazard in Nagar valley, Gilgit Baltistan using Geo-spatial Technique. Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) and Google Earth image has been utilized as input data. Buffer analysis is applied to demarcate the hazard zone and map the elements at risk. The results indicated that Passu Lake has potential to cause GLOF. The volume of the lake has been increased from 788383.79 m^3 (2016) to 892910.494 m^3 (2018). The exposed areas include portions of Karakoram Highway and some villages downstream to Passu Lake along Hunza River. The outcomes of this study will be helpful in reducing the adverse impacts of GLOFs events in Passu sub-watershed. The results can also assist decision makers to develop a mechanism for reliable and cost effective monitoring of glacier lakes and GLOFs hazard and risk assessment using advance geospatial hydrologic/hydraulic modeling techniques.

1. Introduction

Globally, there is a general trend of mountain glacier recession and thinning in response to global warming and climate change. Receding glaciers give rise to glacial lakes when melt water gets accumulated behind semi-permanent structures like moraines and ice. Bursting of these lakes by sudden breach in moraine or ice can cause Glacial Lake Outburst Floods (GLOFs) in the downstream areas. Increase in temperature has caused variations in many natural phenomena particularly expansion, contraction and creation of glacial lakes Hindu Kush Himalayas (HKH) region. GLOFs are causing considerable human life loss, damages to infrastructure and properties in downstream areas (Mernild et al. 2015). The key contributing factors to GLOF hazard and its monitoring are remote sensing, lake volume and rate of formation, reaction of glacier to climatic parameters, activity of glacier, possibility of mass moments into lake, stability, width and height of moraine, and nature and situation down valley. Glacial lakes receive melt-water from parent glacier and related to availability of ice and temperature. The sudden outburst of glacial lakes causes GLOF in downstream area (Pinglot et al. 1994). Consequently, damages to both people and property occur. It is important to keep an eye on the condition of these lakes. Traditional surveys find it very challenging to monitor because of their remote locations and high altitudes (Mool 1995). Since most of the factors connected to glacial lakes can be analyzed using remote sensing data (Bolch et al. 2008). The volume and rate of lake formation, the glacier's response to the climate, its activity, the potential for mass moments into the lake, stability, the width and height of the moraine, and the

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location down valley are the main contributors to glacial lake hazards and its monitoring using remote sensing (Richardson and Reynolds 2000). Several studies have concluded that remotely sensed data is time and cost-effective geo-spatial technique for glacial lake monitoring, development of glacial lake inventory and identification of potential glacial lakes in order to prepare GLOF risk reduction plan (Quincey et al. 2005). Many factors can lead to the breaching of glacial lakes particularly location of lake, stability of slope, seismicity of the area, frequency and magnitude of rock or ice avalanches (Quincey et al. 2007).

The GLOFs pose serious risk to human life, their property and infrastructure (Westoby et al. 2014). In these circumstances, water may leak through sub-glacial tunnels, along the ice edge separating the glacier from the valley side, or by the ice dam breaking mechanically (Clague and Evans 2000). Consequently, a number of studies have adopted an empirical approach to volume calculation from satellite imagery based on known relationships between lake depths, areas and volumes. This allows rapid and simple calculation of lake volumes from widely available satellite imagery, whilst avoiding the necessity for often challenging fieldwork (O'Connor et al. 2001). Therefore, the aim of this study is to assess GLOF hazard and map the elements at risk located in the downstream area. The results of this study can assist decision makers for effective policy formulation that will reduce the risk of GLOFs and enhance community resilience.

2. Materials and Methods

2.1. Study Area

Geographically, Hunza-Nagar valley is situated in Gilgit Baltistan, Northern Pakistan. This study area is located at the altitude of 3000m above mean sea level and extends from 76°0′45.354″E longitude to 73°59′26.466″E longitude and 36°51′38.359″N latitude to 35°55′22.231″N latitude (Afsar et al. 2013). Relatively, shares borders with Afghanistan and China on the northwest and northeast, respectively, and with District Gilgit on the southwest (Fig. 1). This area is distinguished geologically by various rock combinations. This area is known as paradise on Earth and is situated in an area of active tectonics brought on by the collision of the Indian and Eurasian plates (Rehman et al. 2021). It also features a variety of tourist attractions, mineral deposits, and natural resources. The total area of these districts was 14,305.08 km^2. The main tributary of Pakistan's longest river, the Indus, is the Hunza-Nagar River. Around 96% of households in Hunza and Nagar have access to agricultural land and estimate both basic and monetary needs. Upstream population in the Hunza and Nagar sub-basin in the Indus basin relies primarily on natural resources (Dilshad et al. 2019).

2.2. Research Metodology

This study is based on secondary data. Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was downloaded from USGS open source geo-database. Vector data including road network, human settlements and drainage network were digitized in ArcGIS 10.5 by utilizing Google Earth image as base map. The output spatial layers were overlaid on to map the elements exposed to GLOF (Fig. 2).

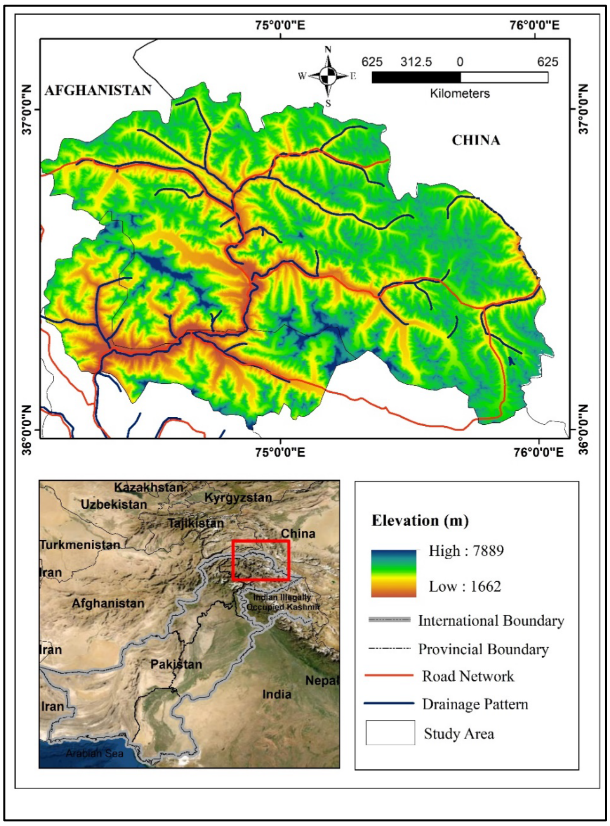

Figure 1. Location of Study Area

2.2.1. Lake Area and Volume Estimation

Area of lake was calculated from the vector mapping of lakes. The years taken were 2016, 2018 and 2020. Five glacial lakes from study region were delineated from Google Earth and further calculation for volume has been done. Although bathymetric survey is considered to be the most accurate method in case of lake volume estimation, but an empirical equation established by Huggel (Huggel et al. 2002) was used in this study. This method has been widely used by many researchers to overcome lack of field data which is hard to collect. Volume of the glacial lake in m^3 is calculated using in Equation (1).

$$V = 0.104A^{1.42} \quad (1)$$

Where "V" is volume of the glacial lake and "A" is area in m^2. The above relationship has been used to estimate the volume and further calculation of maximum discharge in potential lake is calculated by using Equations II and III.

$$PE = 9800 \times h \times V \quad (2)$$

$$Q_{max} = 0.00013 \times PE^{0.6} \quad (3)$$

Where "h" = Height of the moraine dam, "PE" = Potential Energy of the lake, Qmax = Maximum probable flow.

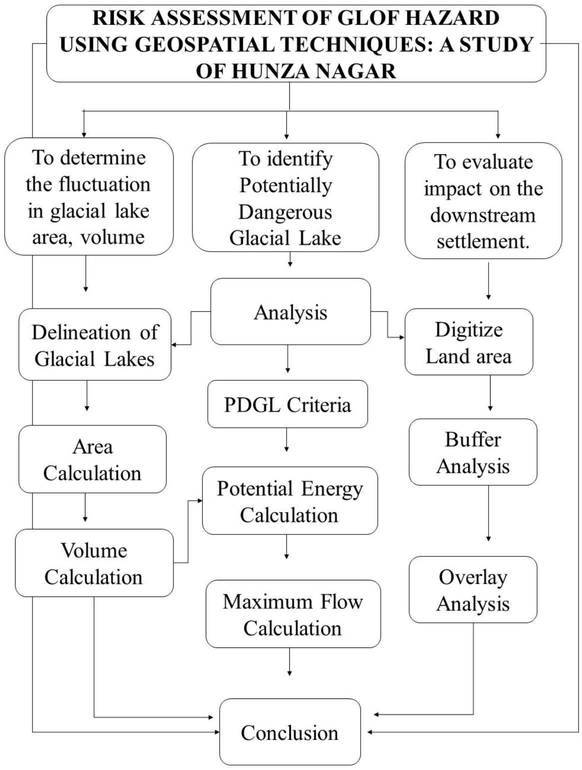

Figure 2. Research design

2.2.2. Identification of Potential Glacial Lakes

The potentially dangerous glacial lakes were identified by utilizing the well-established four parameters including lake area should be greater than 0.500m^2, lake should be attached or in the proximity of parent glacier, supra-glacial lakes should be around them and lakes should have steep slopes (Bairacharya et al. 2007; Mool et al. 2011; Ashraf et al. 2012).

2.2.3. Mapping of Element at Risk

In downstream areas, elements at risk were identified in 500m buffer zone and goe-visualized by overlapping the spatial layers of elements at risk on SRTM DEM. The elements at risk were human settlements, agricultural land and crop, and roads. The results were presented in the form of maps, tables and graphs.

3. Results

This study carried out area mapping around the lakes, downstream hazard vulnerability risk assessment. Bathometry of the lake using Remote Sensing and empirical formula respectively to determine the lake's development processes and assess the prospect of the GLOF from the lake. The surface area and volume of the lake in 2016, 2018 and 2020 are given in the Table 1. Graphs of area and volume are shown in Fig. 3 and Fig. 4. The detailed surface area mapping of glacial lakes is shown in Fig. 5.

Table 1. Area and Volume of Glacial Lakes

Sr. No.	Name	Area (m²)			Volume (m³)		
		2016	2018	2020	2016	2018	2020
1	Kacheli Lake	4211	2128	3362	14576.7391	5530.35544	10579.15
2	Rush Lake	54068	41578	56522	546774.903	376547.392	581850.8
3	Passu Lake	69962	76373	52696	788383.79	892910.494	526771.3
4	Borit Lake	161869	142726	134999	2594452.78	2169840.11	2003378
5	Batura Lake	29788	316754	34597	234515.769	6730676.74	289830.3

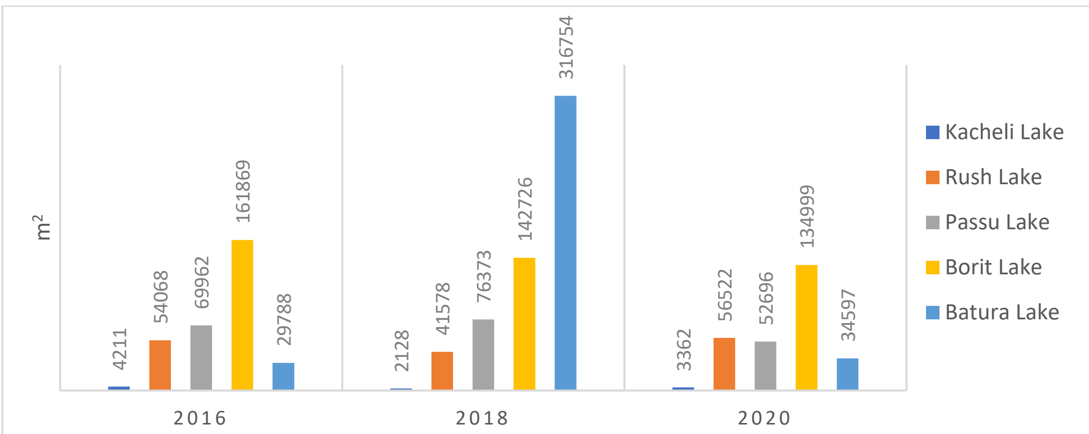

Figure 3. Variation in Area of Glacial Lakes (2016-2020)

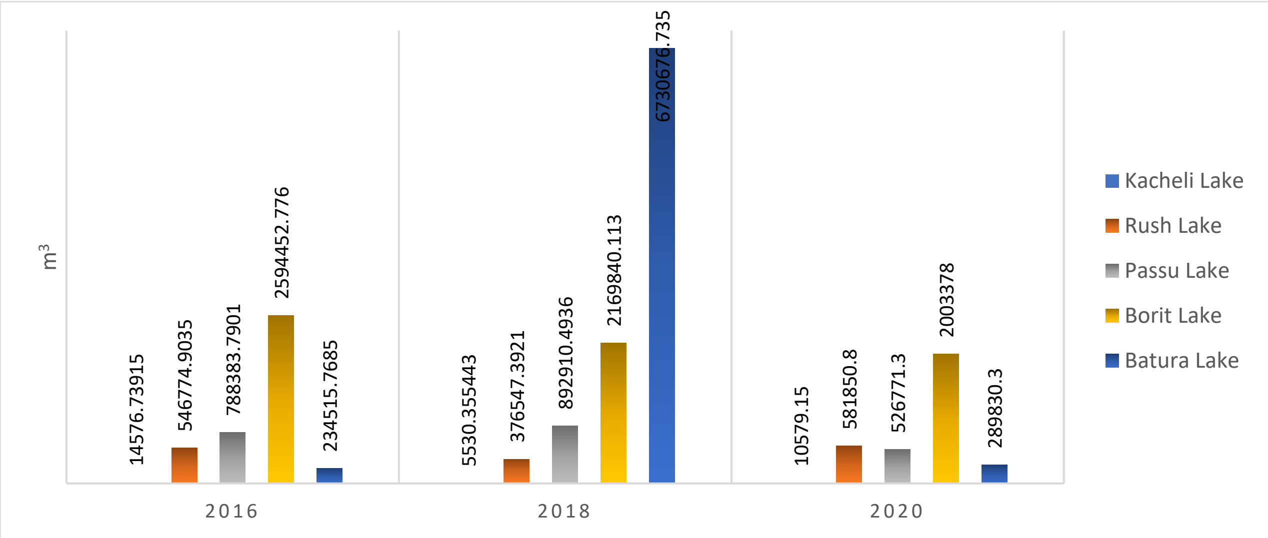

Figure 4. Variation in Volume of Glacial Lakes (2016-2020)

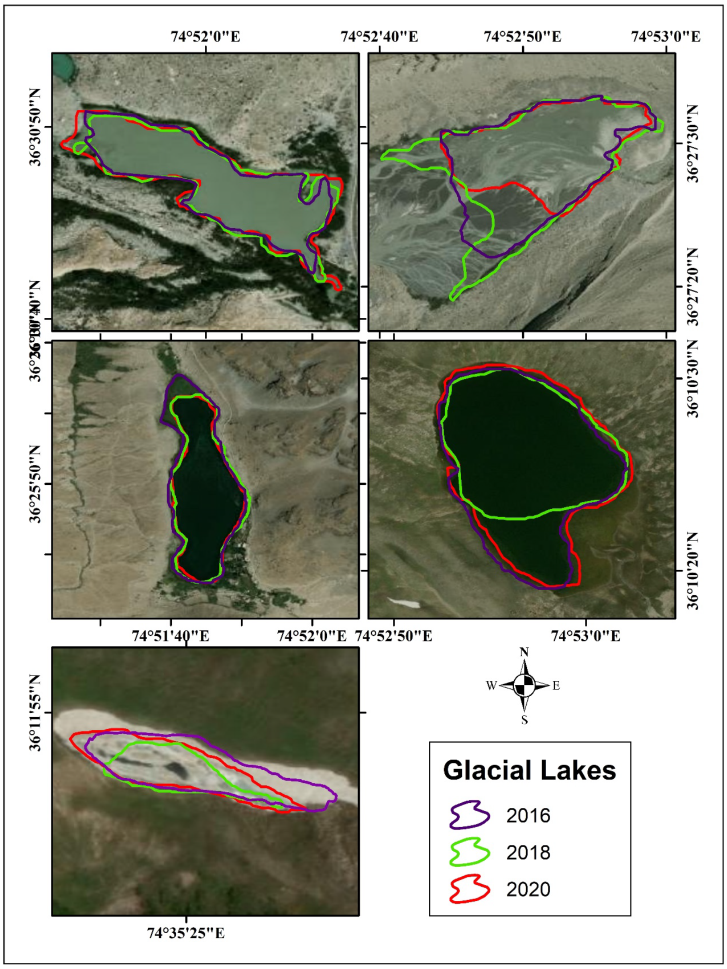

Figure 5. Suface Area mapping of selected lakes (a) Batura Lake, (b) Passu Lake, (c) Borit Lake, (d) Rush Lake, (e) Kacheli Lake

3.1. Potential Glacial Lakes

According to the aforementioned criteria, Passu Lake is only lake that fulfil all the requirements of PDGL. The area of Passu Lake is greater than 0.500 m in all selected years. It is close and connected to the snout of parent glacier i.e. Passu Glacier that is continuously feeding the lake. For the third criterion, it directly falls in Hunza River and major infrastructure and settlement is present in its downstream area. The slope over the area is steep enough to start a major event (Fig. 6).

In 2020, the volume of Passu lake was 526771.3m^3 and the maximum discharge Q_{max} can be upto 869.57 m^3/s if it outburst 100%. If the lake outburst 25% then the maximum discharge will be 217.39 m^3/s. If the lake outburst 50% then the maximum discharge will be 434.79 m^3/s. If the lake outburst 75% then the maximum discharge will be 652.18 m^3/s (Table 2).

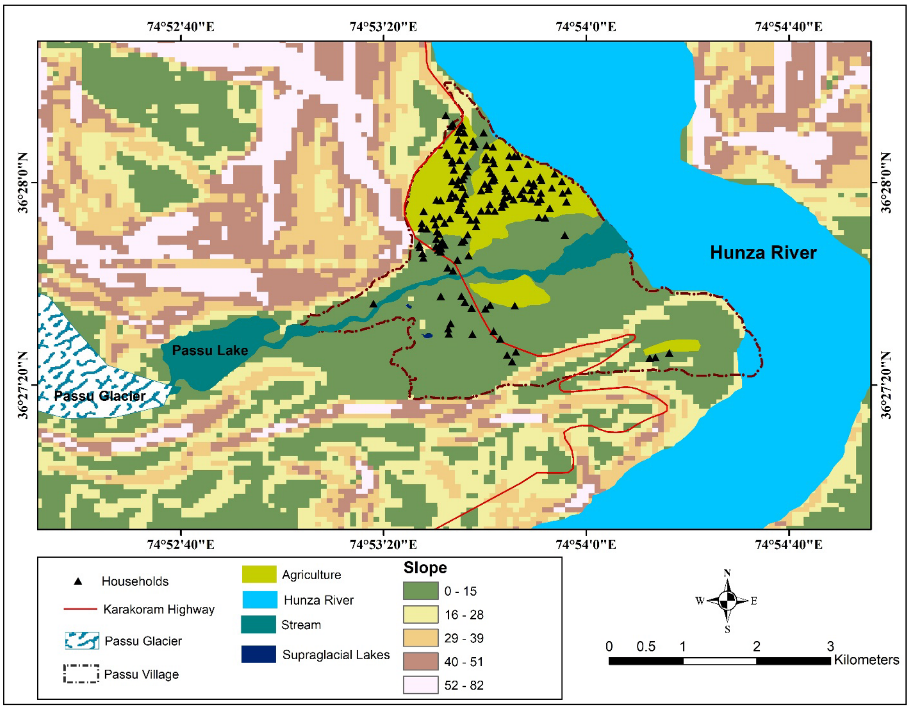

Figure 6. Passu Lake and Elements at Risk in Downstream Area

Table 2. Percentage of Discharge in Passu Lake

% age of discharge	Total Discharge in 2020 (m³/s)
25%	217.39
50%	434.79
75%	652.18
100%	869.57

3.2. Mapping of Potential Areas at Risk

Hazard map was developed by overlaying spatial layers of element at risk, land cover, and 500m buffer zone on slope of the area (Fig. 7). Segments of Karakoram highway are within hazard zones and around 100 houses. The Passu lake outburst in will directly increase the volume of Hunza River and it will eventually cause flooding in downstream areas of Hunza River. Almost 10 villages are exposed to floods in Hunza River.

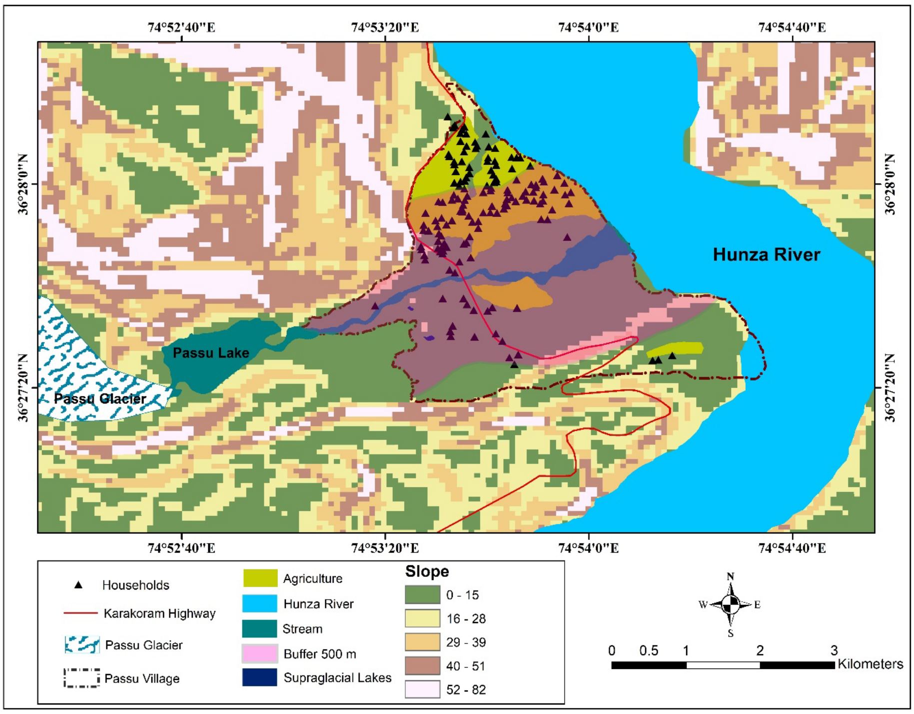

Figure 7. Hazard Zones in Passu Village

4. Discussion

Analysis revealed that geo-spatial techniques are time and cost effective in comparison to filed surveys. In this study, SRTM DEM and Google Earth image has been utilized to identify potential glacial lakes and analyze the volume of lakes by applying vector analysis. Hazard map is prepared depicting elements at risk. A bridge on the Karakoram Highway (KKH) and numerous houses in the Passu village, which is located on the right bank of the Hunza River, were destroyed by at least two outbursts of the 38 km long, east-west oriented Passu Glacier in the past 20 years. Even though the Passu Lake has natural drainage and it seems unlikely that it will erupt, it did so inexplicably, suffering enormous losses. Investigations revealed that a significant amount of water was once stored beneath the glacier's broken tongue, and that under normal circumstances, this water still discharges to the adjacent lake. During the past outburst events, very heavy loads of mud as well as debris flowed downstream under the action of gravity flow destroying the structures on the way (Muneeb et al. 2021).

Analysis further revealed that Passu is potentially dangerous lake in Hunza basin (Qureshi et al. 2022; Rasul et al. 2011). Similarly, out of 5 lakes, Passu is considered to be the most dangerous one in this study. Saifullah et al. states that Passu glacial retreat that increases the flow of water in 2016 and the area and volume increase as compared to past years (Saifullah et al. 2020). These results can also be noticed in this study as the volume in 2016 is higher than 2020, glacial surge could be the reason of decreasing volume in 2020. Anwar and Iqbal shows that the area of Passu glacier is lowest in 2017 from past 23 years that will eventually increase the volume of Passu Lake in those years, this can clearly be seen in this study that the area and volume of Passu in 2018 in highest (Anwar and Iqbal 2018). It is highly recommended to monitor expanding lakes. Traditional surveys find it very challenging to monitor these lakes because of their remote locations and high altitudes (Mool 1995). Sensor based automatic weather stations and Hydro-gauging stations are highly recommended to provide real-time data. This will help in decision making and issuance of early warning. Timely early warning can reduce the chances of potential damages particularly human life.

Furthermore, breaching of glacial lake leads to GLOFs that pose a significant threat to life and infrastructure (Richardson et al. 2000; Westoby et al. 2014). Other potentially dangerous lakes are dammed by ice, either in ice-marginal locations where surface meltwater or water from tributary valleys ponds against the glacier margin or where advancing (often surging) glaciers block river drainage like Kyagar Glacier (Haemmig et al. 2014). In these situations, water may escape through sub-glacial tunnels, along the ice margin between the glacier and valley side or by mechanical failure of the ice dam (Mayer and Schuler 2005; Ives et al. 2010; Aslam et al. 2022).

In short, further research on GLOF risk perception and utilization of high-resolution satellite images and field work is recommended for better results. The results of such studies can assist decision makers for effective policy formulation that will reduce the risk of GLOFs and enhance community resilience against GLOFs.

5. Conclusion

The study concludes that Passu Lake is the most impactful lake for future GLOF hazards in the region. The volume of the lake was 788383.79 m^3 in 2016 that increases to 892910.494 m^3 in 2018 and then decrease to 526771.3 m^3 in 2020. This decrease is due to the instability of parent glacier which is a common phenomenon observed in Karakoram (Karakoram Anomaly). Buffer zone shows 500 m areas most vulnerable that includes agriculture, settlements, and infrastructure. Some settlements along the Hunza River downstream from Passu Lake and stretches of the Karakoram Highway are among the risk regions. These components could sustain harm from any upcoming GLOF event brought on by the Passu Lake outburst. The results of this study will be beneficial in minimizing the negative effects of future GLOF events in the Passu sub-watershed and will be helpful in creating early warning systems in the vulnerable areas. All aspects of disaster management, including mitigation, readiness, response, and recovery, involve hazard and risk maps. The use of hazard and risk maps can help avoid severe events from turning into disasters, but they cannot stop a catastrophic phenomenon from occurring. Even though it is often difficult to prevent natural disasters like GLOFs, having understanding of their nature and potential scope can help DM authorities prepare for and respond to emergency situations and disasters. The effects of these catastrophes are also mitigated by increased preparedness.

It is also concluded form the study that further research on GLOF risk perception is recommended. Utilization of high resolution satellite images and field work is also recommended. The results of this study can assist decision makers for effective policy formulation that will reduce the risk of GLOFs and enhance community resilience against GLOFs.

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