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Geospatial assessment of GLOF hazards in Hunza-Nagar, Gilgit-Baltistan, Pakistan

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Abstract

Globally, rising temperatures have led to variations in various natural phenomena, most notably the formation, shrinkage, and expansion of glacial lakes in the Hindu Kush Himalayas (HKH) region. A number of these lakes have recently been outburst, creating Glacial Lake Outburst Floods (GLOFs) that have severely damaged downstream infrastructure and caused significant loss of life. This study uses geospatial techniques to evaluate the GLOF hazard in Gilgit Baltistan's Nagar Valley. As input data, Google Earth Imagery and the Digital Elevation Model (DEM) from the Shuttle Radar Topographic Mission (SRTM) have been used. The hazard zone is marked off and the components that are at risk are mapped using buffer analysis. The findings suggested that GLOF might be caused by Passu and Borit Lakes. The lakes' respective volumes have increased from 1425005 m^3 and 1944566 m^3 in 2019 to 1983911 m^3 and 2255715 m^3 in 2022. Parts of the Karakoram Highway and a few villages downriver to the Passu and Borit Lakes along the Hunza River are among the risked areas. The results of this research will be useful in lessening the negative effects of GLOF events in the sub-watersheds of Passu and Borit. The findings can also help policymakers create a system for the advanced geospatial hydrologic/hydraulic modeling techniques that will enable the safe and economical monitoring of glacier lakes and the hazard and risk assessment of GLOFs.

1. Introduction

Globally, mountain glaciers are generally receding and thinning as a result of climate change and global warming. For hundreds of millions of people downstream, the HKH alpine glaciers provide a replenishable natural freshwater reserve. Since the latter half of the 20th century, the glaciers in Pakistan's mid-latitude region have receded due to an acceleration of global warming [1]. Glacial lakes are created when meltwater accumulates behind semi-permanent features like ice and moraines, resulting from retreating glaciers. Glacial Lake Outburst Floods (GLOFs) can occur downstream when these lakes suddenly burst due to a breach in the ice or moraine. The Hindu Kush Himalayas (HKH) region's glacial lakes have expanded, contracted, and created new lakes as a result of temperature increases. Significant human casualties and property and infrastructure damage are being caused by GLOFs in downstream areas [2]. Over 15% of the area loss in their connected glaciers has probably been caused by glacier-connected lakes, which have probably accelerated the glacial retreat through thermal energy transmission. However, sizable glacial retreats caused them to separate from their pro-glacial lakes, which seemed to stabilize the Himalayan lakes. Because of the possibility of their eruptions, ongoing expansions in the lakes associated with debris-covered glaciers require further monitoring [3]. Remote sensing, lake volume and rate of formation, glacier activity, and response of the glacier to climatic parameters, potential for mass moments into the lake, stability, width and height of the moraine, and the nature and circumstances down valley are the main contributing factors to the GLOF hazard and its monitoring. The parent glacier's meltwater flows into glacial lakes, which are dependent on temperature and ice availability. GLOF occurs downstream as a result of glacial lakes suddenly erupting [4].

As a result, there are injuries to both persons and property. It is critical to monitor the state of these lakes. Traditional surveys are extremely difficult to monitor due to their high altitudes and remote locations [5]. Since, remote sensing data can be used to analyze the majority of the factors related to glacial lakes [6]. The main factors that contribute to glacial lake hazards and their monitoring through remote sensing are the volume and rate of lake formation, the glacier's activity and response to the climate, stability, the possibility of mass moments into the lake, the width and height of the moraine, and the location down valley [7]. In order to prepare a GLOF risk reduction plan, it has been determined by several studies that remotely sensed data is a time and cost-effective geospatial technique for glacial lake monitoring, development of an inventory of glacial lakes, and identification of potential glacial lakes [8]. Numerous factors, including the lake's location, slope stability, seismic activity in the area, and the frequency and intensity of rock or ice avalanches, can cause glacial lakes to break [9].

The infrastructure, property, and lives of people are seriously at risk from the GLOFs [10]. Under these conditions, water may seep through subglacial tunnels, along the glacier's edge where it separates from the valley floor, or through the mechanical failure of an ice dam [11]. As a result, several studies have used an empirical method based on established correlations between lake depths, areas, and volumes to calculate volumes from satellite imagery. As a result, lake volumes can be quickly and easily calculated using publicly available satellite imagery, negating the need for labor-intensive fieldwork [12]. Thus, this study's objective is to map the components at risk situated in the downstream area and evaluate the GLOF hazard. The study's findings can help policymakers create policies that will lessen the likelihood of GLOFs and increase community resilience.

2. Study Area

Geographically speaking, the Hunza-Nagar Valley is located in Northern Pakistan's Gilgit Baltistan. This study area spans from 76°0′45.354′E longitude to 73°59′26.466′E longitude and from 36°51′38.359′N latitude to 35°55′22.231′N latitude, all at an altitude of up to 7761 meters above mean sea level [13]. Relatively, it borders District Gilgit on the southwest and Afghanistan and China on the northwest and northeast, respectively (Figure 1). The different rock combinations in this area give it its geological distinctiveness. Situated in an area of active tectonics caused by the collision of the Indian and Eurasian plates, this region is referred to as "paradise on Earth." [14]. It also has a wide range of natural resources, mineral deposits, and tourist attractions. These districts covered 14,305.08 km^2 in total. The Hunza-Nagar River is the principal tributary of the Indus, the longest river in Pakistan. In Hunza and Nagar, 96% of households estimate that they have access to agricultural land and that they need money in addition to basic necessities. Natural resources are the main source of income for the upstream population in the Indus basin's Hunza and Nagar subbasins [15].

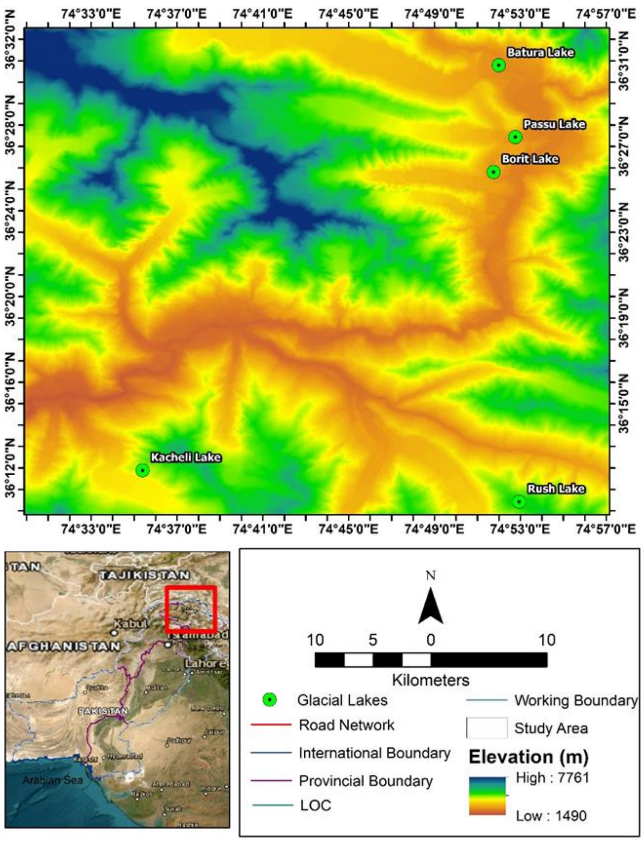

Figure 1. Location map of the study area.

3. Method

The secondary data used in this study. The digital elevation model (DEM) from the Shuttle Radar Topographic Mission (SRTM) was obtained from the USGS open-access geodatabase. ArcGIS 10.5 was used to digitize vector data, such as the road network, human settlements, and drainage network, using a Google Earth Imagery as the base map. The elements exposed to GLOF were mapped using the output spatial layers superimposed (Figure 2).

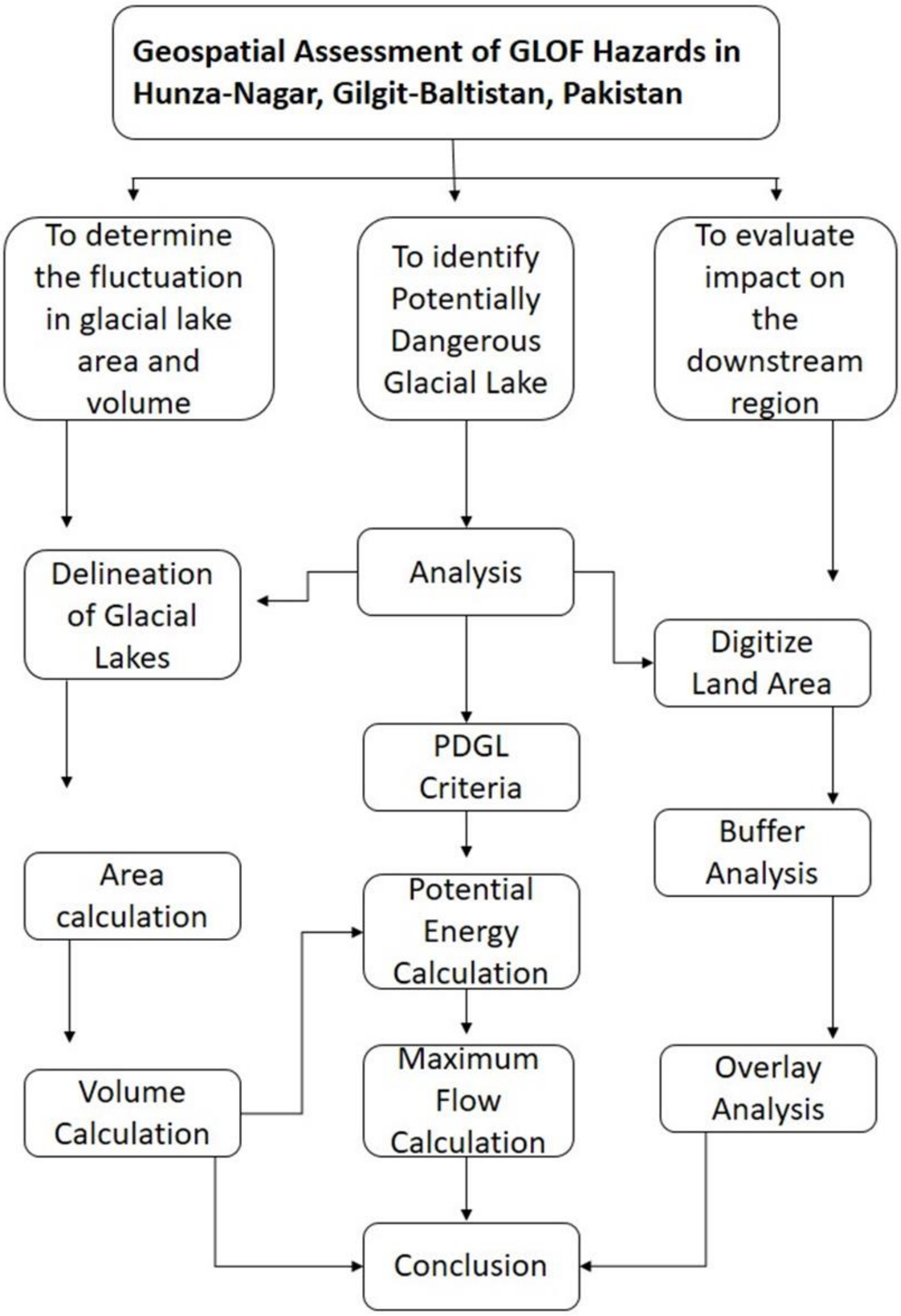

Figure 2. Research design.

3.1 Lake area and volume estimation

The vector mapping of lakes was used to calculate the area of each lake. These five years were used: 2019, 2020, 2021 and 2022. Five glacial lakes within the study area were identified using Google Earth, and additional volume calculations were performed. Despite the fact that bathymetric survey is thought to be the most accurate technique for estimating lake volume, Huggel's empirical equation [16] was employed in this study. Many researchers have utilized this technique extensively to get around the challenge of gathering difficult-to-collect field data. Volume of the glacial lake in m^3 is calculated using in Equation 1.

$$V = 0.104A^{1.42} \tag{1}$$

where "A" is the area in square meters and "V" is the glacial lake's volume. Equations 2 and 3 are used to determine the maximum discharge in a potential lake after the volume has been estimated using the aforementioned relationship.

$$PE = 9800 \times h \times V \tag{2}$$

$$Q_{max} = 0.00013 \times PE^{0.6} \tag{3}$$

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

3.2 Identification of potential glacial lakes

Using the well-established four criteria according to [17-18] PGLs were identified,

- A lake's area should be greater than 0.500 m^2
- Lake be attached to or near the parent glacier
- Supra-glacial lakes should surround the lakes
- The lakes have steep slope

3.3 Mapping of element at risk

Elements at risk in downstream areas were located in a 500 m buffer zone and were visualized by superimposing their spatial layers on an SRTM DEM. Roads, agricultural land and crops, and human settlements were the elements at risk. Tables, graphs, and maps were used to display the findings.

4. Results

This study assessed the risk of downstream hazard vulnerability and conducted area mapping surrounding the lakes. To ascertain the lake's development processes and evaluate the likelihood of the GLOF emerging from the lake, bathometry of the lake was conducted using remote sensing and empirical formulas, respectively. Table 1 provides the lake's surface area and volume for the years 2019, 2020, 2021 and 2022. Figure 3 and 4 display area and volume graphs. Figure 5 displays the comprehensive surface area mapping of glacial lakes.

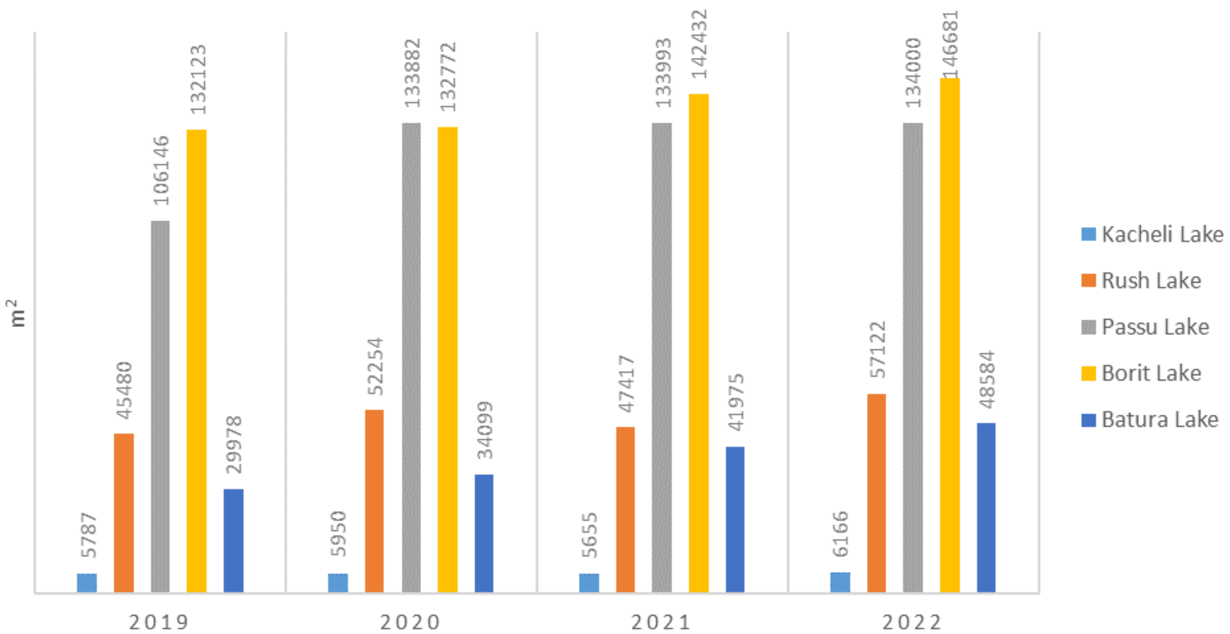

Figure 3. Variation in area of Glacial Lakes (2019-2022).

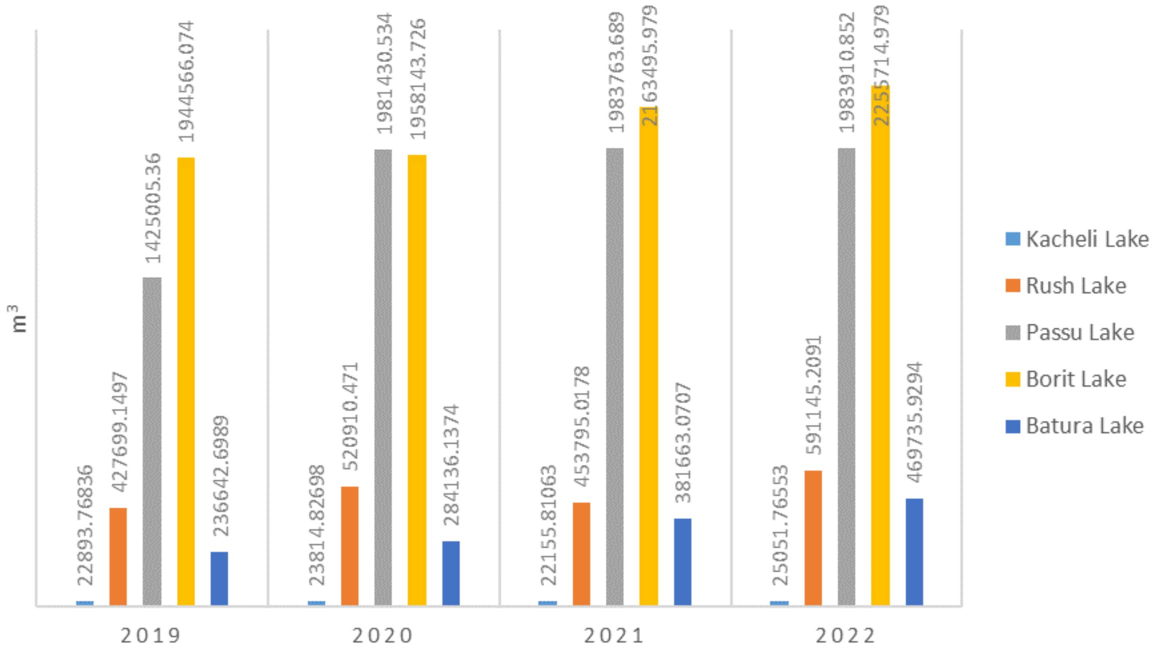

Figure 4. Variation in volume of glacial lakes (2019-2022).

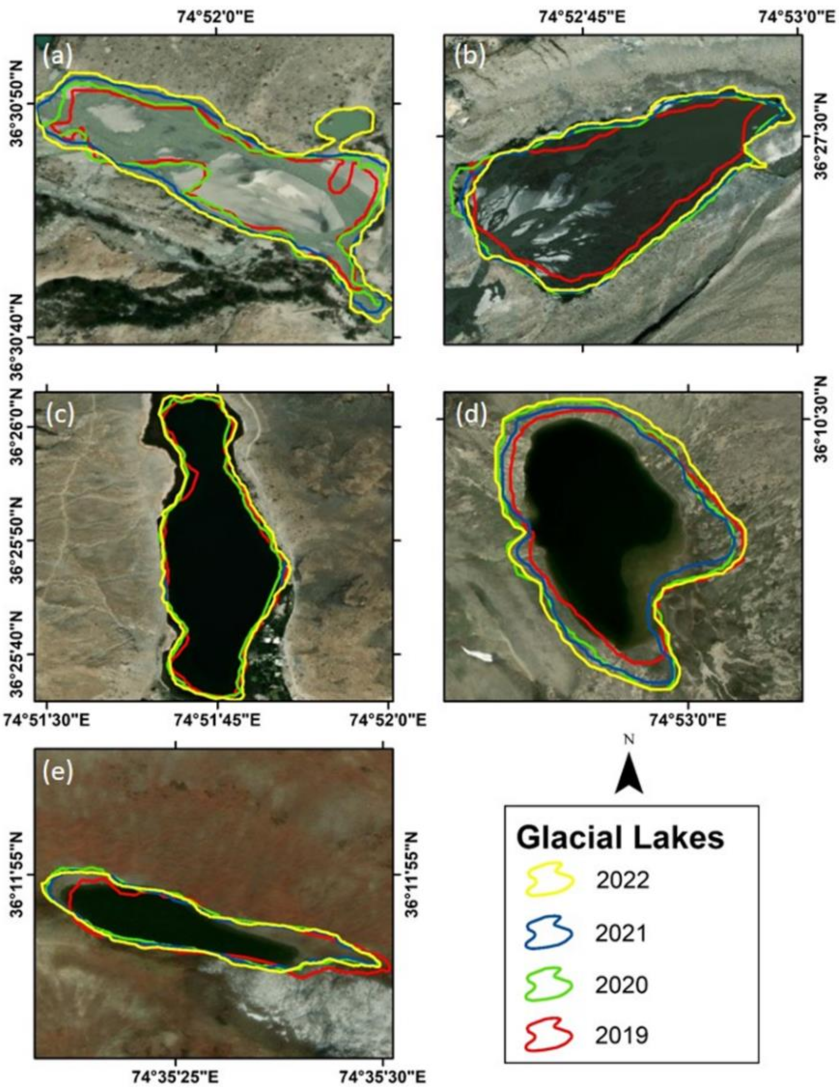

Figure 5. Surface area mapping of selected lakes (a) Batura Lake, (b) Passu Lake, (c) Borit Lake, (d) Rush Lake, (e) Kacheli Lake.

Table 1. Area and volume of glacial lakes.

	Area (m²)				Volume (m³)			
Glacial Lakes	2019	2020	2021	2022	2019	2020	2021	2022
Kacheli Lake	5787	5950	5655	6166	22893.77	23814.83	22155.81	25051.77
Rush Lake	45480	52254	47417	57122	427699.1	520910.5	453795	591145.2
Passu Lake	106146	133882	133993	134000	1425005	1981431	1983764	1983911
Borit Lake	132123	132772	142432	146681	1944566	1958144	2163496	2255715
Batura Lake	29978	34099	41975	48584	236642.7	284136.1	381663.1	469735.9

4.1 Potential glacial lakes

The only lakes that meet all of PDGL's requirements are Passu and Borit Lakes, based on the previously mentioned criteria. In every year that was chosen, the area of Passu and Borit Lakes is greater than 0.500 m. They are near and linked to the parent glacier's snout, Passu Glacier, which feeds both lakes continuously, and Ghulkin Glacier, which feeds Borit Lake. Regarding the third criterion, they are situated directly in the Hunza River, and the downstream area has significant infrastructure and populated areas. A significant event could be triggered by the area's steep slope (Figure 6-7).

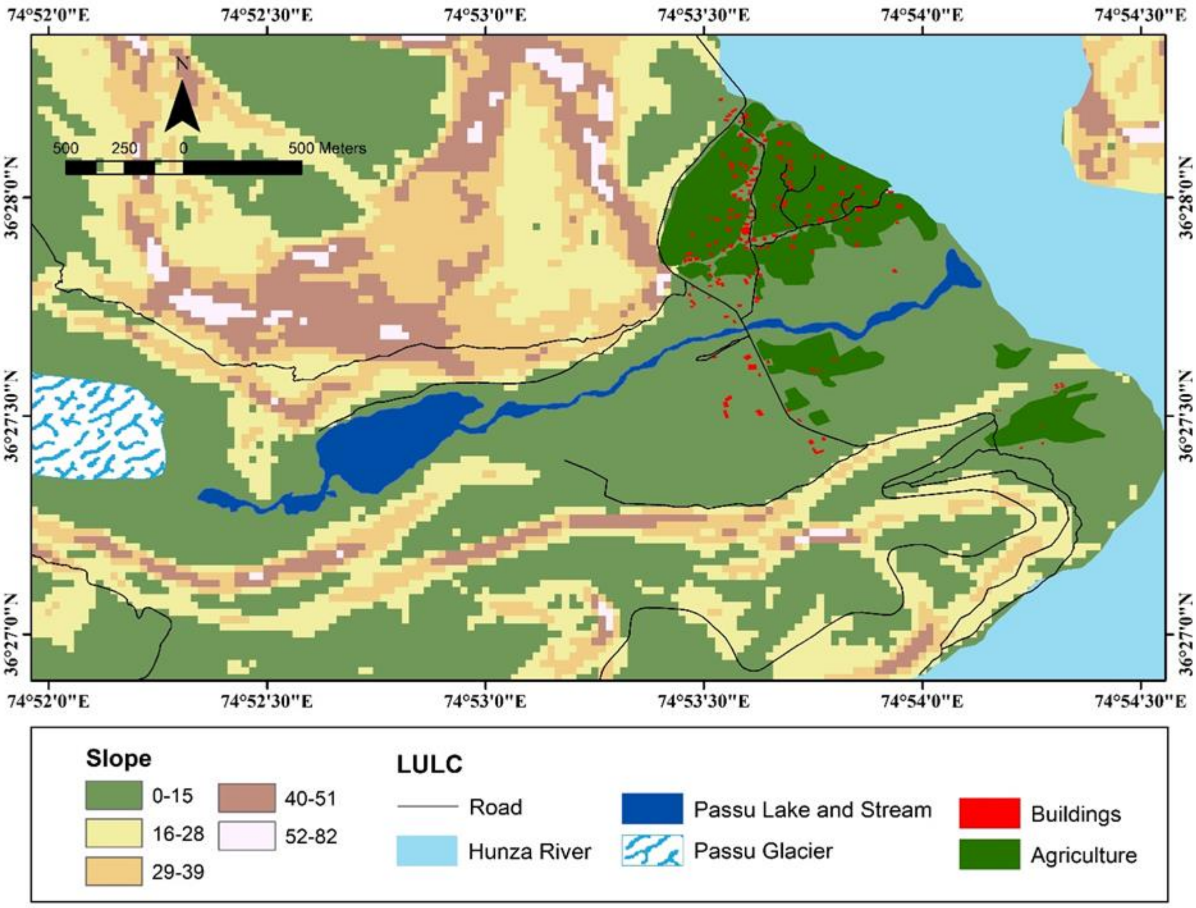

Figure 6. Passu Lake and elements at risk in downstream area.

In 2022, the volume of Passu Lake was 1983911m³ and the maximum discharge Q_{max} could be up to 20601.73 m³/s if its outburst was 100%. If the lake outburst was 25% then the maximum discharge would have been 5150.43 m³/s. If the lake outburst was 50% then the maximum discharge would have been 10300.87 m³/s. If the lake outburst was 75% then the maximum discharge would have been 7725.65 m³/s (Table 2).

Table 2. Percentage of discharge in Passu Lake.

	25%	50%	75%	100%= Q_{max}
2019	4222.99	8445.99	6334.49	16891.97
2020	5146.57	10293.14	7719.85	20586.27
2021	5150.20	10300.41	7725.31	20600.82
2022	5150.43	10300.87	7725.65	20601.73

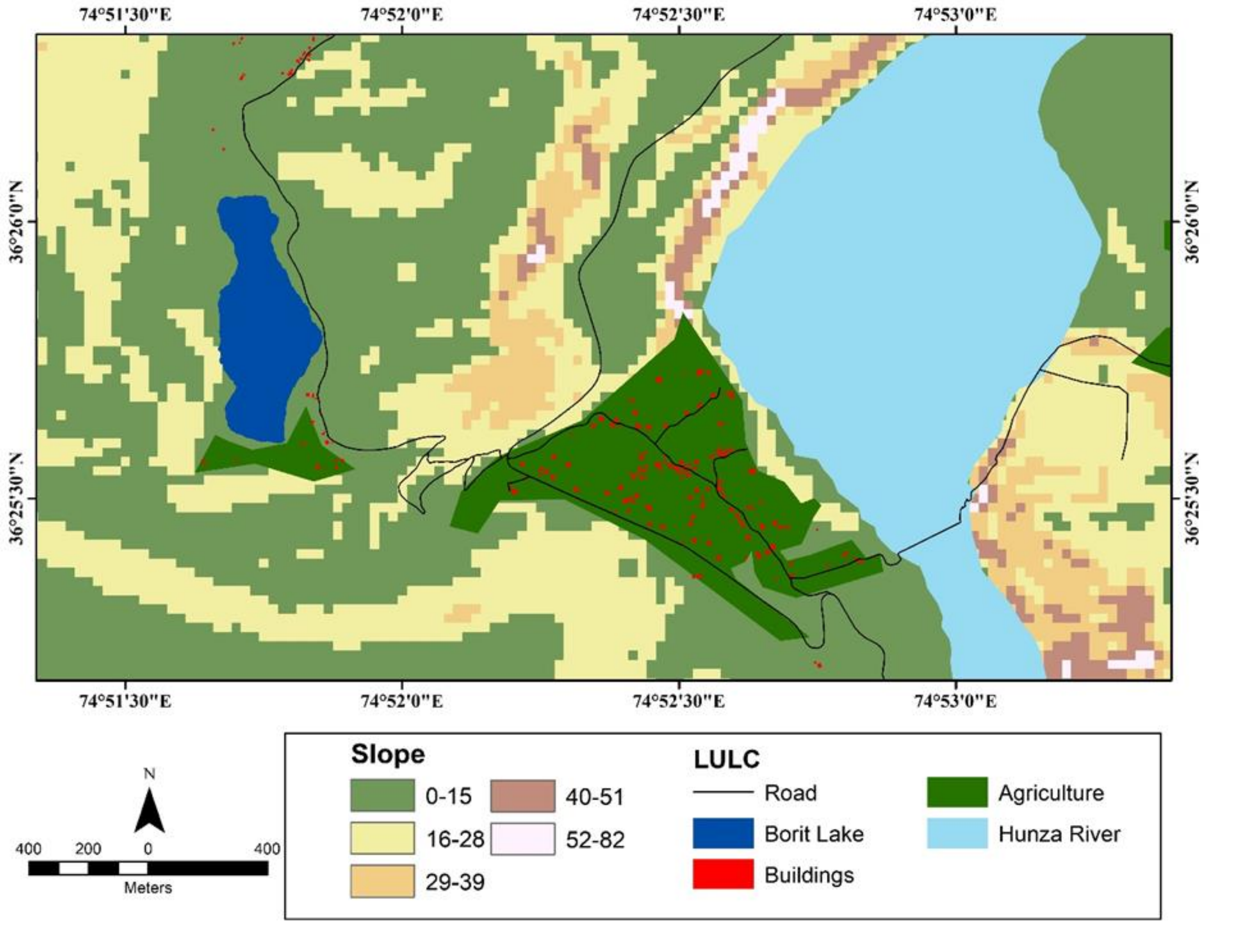

Figure 7. Borit Lake and elements at risk in downstream area.

Similarly, in 2022, the volume of Borit Lake was 2255715m^3 and the maximum discharge Qmax could be up to 23820.25 m^3/s if its outburst was 100%. If the lake outburst was 25% then the maximum discharge would have been 5955.06 m^3/s. If the lake outburst was 50% then the maximum discharge would have been 11910.13 m^3/s. If the lake outburst was 75% then the maximum discharge would have been 17865.19 m^3/s [Table 3].

Table 3. Percentage of discharge in Borit Lake.

	25%	50%	75%	100%= Q_{max}
2019	5447.65	10895.31	16342.96	21790.61
2020	5470.44	10940.89	16411.33	21881.78
2021	5807.77	11615.54	17423.31	23231.09
2022	5955.06	11910.13	17865.19	23820.25

4.2 Mapping of potential areas at risk

A hazard map was created by superimposing land cover, 500 and 1000 meter buffer zones, and element at risk spatial layers on the area's slope (Figure 8-9). There are sections of the Karakoram highway that are at risk due to any possible GLOF event. Also, Passu Village is at downstream region of Passu Lake and Hossaini Village at the downstream region of Borit Lake due to which there are near 100 homes that are in danger zones. The outburst of the Passu and Borit lakes will directly raise the Hunza River's volume, which will ultimately result in flooding in the river's downstream regions. The Hunza River can flood almost ten villages.

5. Discussion

When compared to field surveys, analysis showed that geospatial techniques are more economical and time-efficient. In this study, possible glacial lakes have been identified using SRTM DEM and Google Earth images, and the volume of lakes has been analyzed using vector analysis. A prepared hazard map shows the components that are at risk. At least two of the 38 km long, east-west oriented Passu Glacier's outbursts in the last 20 years have destroyed a bridge on the Karakoram Highway (KKH) and many houses in the Passu village, which is situated on the right bank of the Hunza River. The Passu Lake erupted mysteriously, causing massive losses, despite having natural drainage and appearing unlikely to do so. Studies showed that a sizable volume of water was once held beneath the fractured tongue of the glacier, and that this water still flows to the nearby lake in normal circumstances. Very large amounts of mud and debris flowed downstream during previous outburst events due to gravity flow, demolishing the buildings along the route [19].

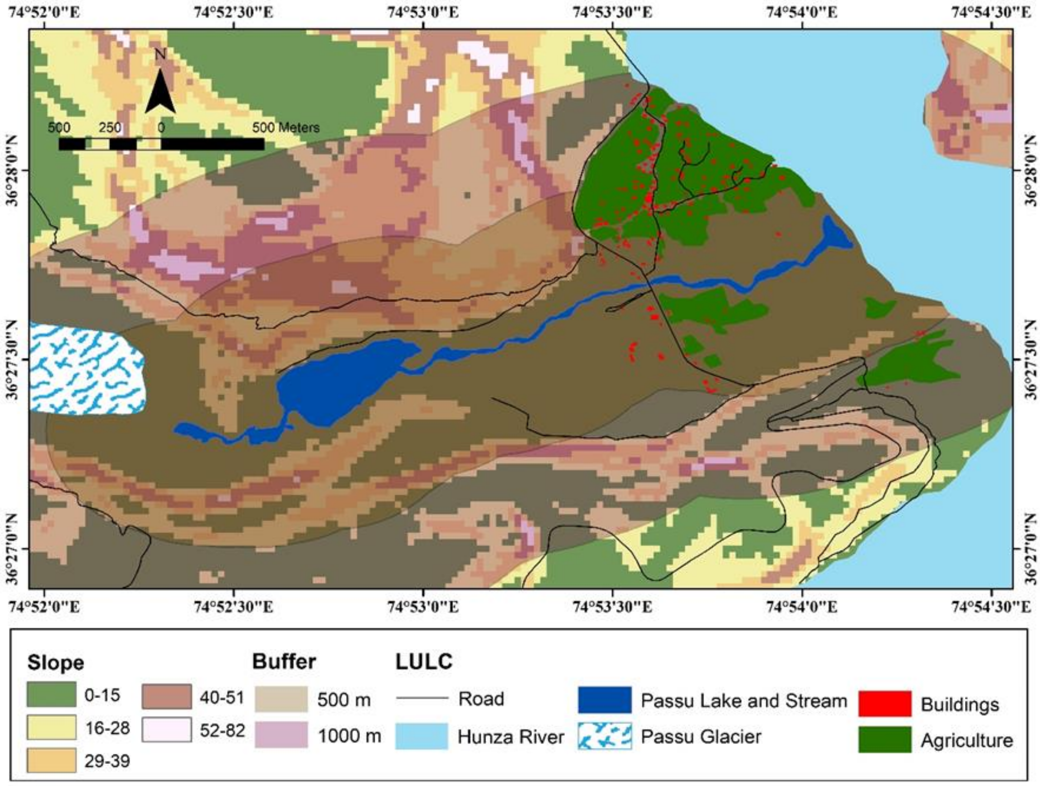

Figure 8. Hazard zones in Passu Village.

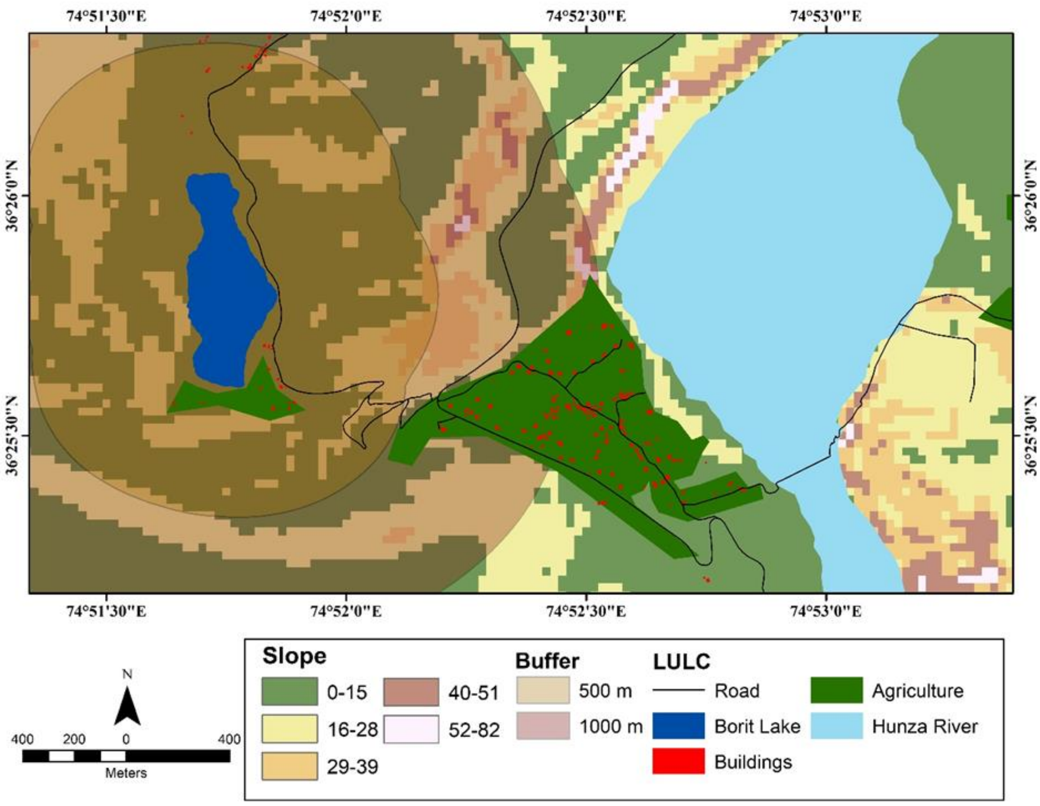

Figure 9. Hazard zones in Hossaini Village.

Analysis further revealed that Passu is potentially dangerous lake in Hunza basin. Similarly, Borit Lake is also considered to be one of the most dangerous according to this study. 2008 saw floods on April 6, May 21, May 25, and June 14 from the south side of the Ghulkin Glacier terminus (right). Although there were media reports of cattle losses on April 6, the specifics of the incident remain unknown. The event on May 21 is believed to have mostly flowed down the current meltwater channel without causing any damage. The biggest events occurred on May 25 and June 14, eroding a channel through a portion of Ghulkin Village. The loss of livestock, orchards, arable crops, four houses, six cattle sheds, and damage to the Karakoram Highway were the immediate effects. Also, a drought struck Hossaini Village in 2009 as a result of damage to four irrigation channels [20].

It is strongly advised to keep an eye on growing lakes. Due to their high elevation and remote locations, these lakes are very difficult for traditional surveys to monitor. For real-time data, sensor-based automatic weather stations and hydro-gauging stations are highly recommended. This will support early warning system issuance and decision-making. Early and prompt warning can lessen the likelihood of possible harm, especially to human life [21-22]. Based on this study, Passu and Borit are the two most dangerous lakes out of five. According to Saifullah et al., the Passu glacial retreat increased water flow in 2016 and increased both area and volume compared to previous years [23]. These findings are also evident in this study, where the volume in 2016 is greater than in 2020; the volume in 2020 may have decreased due to a glacial surge. According to Anwar and Iqbal's research, the Passu glacier's area was at its lowest point in 2017 out of the previous 23 years, which ultimately led to an increase in Passu Lake's volume during those years. This study also makes it evident that the Passu glacier's area and volume were at their highest in 2018 [24].

Moreover, glacial lake breaches result in giant landslides (GLOFs), which are extremely dangerous for both infrastructure and human life. Other possibly hazardous lakes are frozen over, either in ice-marginal areas where water from tributary valleys or surface meltwater ponds against the glacier edge, or in areas where advancing (often surging) glaciers obstruct river drainage, such as Kyagar Glacier [25]. In these circumstances, water may leak out of the ice dam due to mechanical failure, subglacial tunnels, or the ice margin separating the glacier from the valley side [26-28].

To put it briefly, more investigation into the perception of GLOF risk and the application of high-resolution satellite imagery and fieldwork is advised for improved outcomes. The outcomes of these studies can help policymakers create effective policies that will lower the likelihood of GLOFs and increase community resilience to them.

6. Conclusion

According to the study's findings, the lakes that will have the biggest effects on the region's potential GLOF hazards are Passu and Borit. The lakes' respective volumes in 2019 were 1425005 m^3 and 1944566 m^3, which increased to 1981431 m^3 and 1958144 m^3 in 2020, and subsequently to 1983911 m^3 and 2255715 m^3 in 2022. The buffer zone displays the 500 m most vulnerable areas, which are made up of infrastructure, habitations, and agriculture. The risk areas include sections of the Karakoram Highway and a few communities downstream of the Passu and Borit Lakes on the Hunza River. Any future GLOF event caused by the Passu and Borit Lakes outburst could cause damage to these components.

The Passu and Borit sub-watersheds will benefit from the study's findings in reducing the detrimental effects of future GLOF events and in developing early warning systems in the areas that are vulnerable. Hazard and risk maps are used in all facets of disaster management, such as preparedness, mitigation, response, and recovery. Although they can prevent severe events from becoming disasters, hazard and risk maps are powerless to stop a catastrophic phenomenon in its tracks. Even though it is frequently impossible to prevent natural disasters like GLOFs, DM authorities can better prepare for and respond to emergencies and disasters by having an understanding of the nature and potential scope of these events. Enhanced readiness also helps to lessen the effects of these disasters. The study also concludes that more research on how people perceive GLOF risk is advised. It's also advised to use fieldwork and high-resolution satellite imagery. The findings of this study can help policymakers create effective policies that will lower the likelihood of GLOFs and increase community resilience to them.

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Author contributions

Ahsan Iqbal: Conceptualization, Methodology, Writing-Original draft preparation. **Aiman Nisar:** Data curation, Software, Validation. **Shakeel Mahmood:** Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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