6th Intercontinental Geoinformation Days

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Spatio-temporal appraisal of glacial lakes, susceptibility analysis and potentials of glacial lake outburst floods in the peri-glacial environment of Western Himalayas

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Keywords
Glacial Lake
Glacial Lake Outburst Flood
Astore Drainage Basin
Analytical Hierarchy Process
Susceptibility Mapping

Abstract

This study is focused on Spatio-temporal monitoring of glacial lakes, susceptibility analysis and potentials of glacial lake outburst floods (GLOF) in the Periglacial environment of western Himalayas. In the study region, parallel to recurrence of GLOF events, the number and volume of glacial lakes in the peri-glacial area are increasing. In western Himalayas, 52 out of 2,600 glacial lakes are considered as potentially dangerous. Astor Drainage Basin (on which the present study is based), host numerous glaciers and glacial lakes whereas, Glacial Lake Outburst Floods (GLOFs) are recurrently occurring phenomenon. It has a geographical area of about 3988.7 km^2 and the altitude varies from 1237m to 8105m amsl. The study area receives heavy precipitation and most of the peaks remain under snow year-round. The data were collected from Astore, Rama, and Rattu met stations, while discharge data were obtained from Doyian station. It has been calculated that there are a total of 372 small and large glaciers spread over an area of 239.59 Km^2 making 6% of the total area. The analysis revealed that the number of glacial lakes has been increased from 120 in 1989 to 128 in 2019, whereas the areal extent of the glacial lakes has been increased from 4.75 km^2 to 5.861 km^2, respectively. During the study period, out of total glacial lakes, 2 (two) were vanished whereas, 10 new lakes were formed. Furthermore, for carrying out susceptibility analysis, twelve GLOFs factors including slope, lake area expansion, aspect, lake type, distance between glacier's snout and lake, precipitation, elevation, distance to settlement, land surface temperature, distance to road network, fault lines and surface lithology were prepared and weight were assigned using Saaty's Scale. Subsequently, the final GLOF susceptibility zonation map was developed and the results were classified into free zone (20.340%: 796.4622 km^2), very low susceptible area (32.272%: 1263.6660 km^2), low (25.644%: 1004.1560 km^2), moderate (13.610%: 532.9245 km^2), high (6.154%: 241.0049 km^2) and very high susceptible zone (1.9%: 77.4288 km^2) of the total geographical area of Astore Drainage Basin, respectively. In the study area, the GLOF event frequently hit the downstream communities and poses serious threat to vulnerable communities. It is therefore, monitoring glacial lakes and GLOF susceptibility zonation may assist DRR managers and policy makers in taking appropriate measures for the reduction of GLOFs related damages.

1. Introduction

Global warming patterns are causing glaciers to retreat (Zemp et al., 2015). As a result, several glacial lakes form in, around, and under the glacier (Linsbauer et al., 2015). According to previous research, glaciers with low flow velocity or those that are stationary and have a low surface slope angle are more vulnerable to lake formation (Frey et al., 2010). These lakes grow in size and number (Wang et al., 2015), end in a cataclysmic manner (Korup and Tweed, 2007), and their consequences increase the risk of Glacial Lake Outburst Floods. A Glacial Lake Outburst Flood (GLOF) is "A form of outburst flood that occurs when the dam containing a glacial lake fails" (Hakeem et al., 2018).

Glacial lakes are found in northern Pakistan's high mountain ranges. In the Hindu Kush Himalayas (HKH) area of the country, there are currently around 2,600 glacial lakes (Rehman, 2015). According to the inventory, developed by International Centre for Integrated Mountain Development (ICIMOD), 2,500 glacial lakes were identified in ten river basins of Pakistan's HKH

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Cite this study

Rahman, A. (2023). Spatio-temporal appraisal of glacial lakes, susceptibility analysis and potentials of glacial lake outburst floods in the peri-glacial environment of Western Himalayas. Intercontinental Geoinformation Days (IGD), 6, 256-259, Baku, Azerbaijan

region in 2005 (ICIMOD, 2005). Nonetheless, it was estimated to be 2,420 in 2010, with 52 of them being deemed potentially hazardous. Cirque type accounts for 25% of these lakes, while End Moraine Dammed accounts for 62% (ICIMOD, 2010). The Indus, Astore, and Gilgit River Basins form the bulk of these lakes. GLOF has been increasing in this area as one of the more common natural phenomena (Ashraf et al., 2012). GLOF incidents were more common during the years 1900-1910 and 2000-2010, according to the existing records. One of the most forceful GLOF came from the Karamber valley glacier in June, 1905. The valley has a long history of generating GLOF events (Iturrizaga, 2005). In the second decade (2000-2010), five GLOF events were recorded from the Hunza valley's Gojal village alone in 2008 (Rehman, 2015).

The HKH region is highly vulnerable to glacial lake outburst floods (GLOF), and there has been very little work done here so far. Furthermore, no such research has been done in the Astore Drainage Basin. The aim of this study is to conduct a Spatio-temporal distribution of glacial lakes over a thirty-year period (from 1989 to 2019) and to conduct the susceptibility analysis of Glacial Lake Outburst Flood (GLOF) of the study area by using the available data and AHP. The proposed study's findings would act as a baseline for future research. It will also give Disaster Risk Reduction (DRR) administrators and policymakers an insight into how to minimize future damages.

2. Method

This study is conducted in Astore Drainage Basin, located in Himalayas. The study area spans between 34º 46' 31" to 35º 38' 38" North latitude and 74º 24' 12" to 75º 14' 52" East longitude. The Astore Drainage Basin is bordered on the north by Gilgit district, on the south by Neelum valley, on the east by Skardu district, and on the west by Diamir. It covers a total area of 3988.7 Km^2. The basin's elevation varies between 1237 and 8105 meters above sea level. Astore, Rama, and Rattu are the three meteorological stations, while Doyian is the only hydrometric station. There are 372 glaciers in the study area, covering a total area of 239.59 km^2. The Astore Sub-basin has the lowest ice reserves in the Upper Indus Basin (UIB), with just 16.88 km^3 of ice (ICIMOD, 2011). In the winter, this area gets heavy precipitation, and most of the peaks are snow-covered all year (Ahmad et al., 2018).

Inventories are the most basic form of mapping, and they are the first step in studying and analyzing any phenomenon. Landsat satellite images with a spatial resolution of 30m and some with 15m (panchromatic) were used to compile glacial lake inventories in Astore Drainage Basin for the observation years 1989, 1999, 2009, and 2019.

The GLOF susceptibility map was created using twelve factors that were chosen for this study based on their effectiveness and availability. Slope, aspects, elevation, lake type, lake area extension, and distance between glacier's snout and glacial lake, as well as distance to road network, distance to settlement, precipitation, land surface temperature (LST), fault line, and surface lithology, are all factors to consider. Data was gathered from secondary sources to achieve the study's objectives. It contains data from the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM), Landsat Imageries, Google Earth Images, a Lithological Map, and Meteorological data from Tropical Rainfall Measuring Mission (TRMM) and Astore Meteorological Station. To assess GLOF susceptibility in the study area, a systematic methodology combining Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) was used.

3. Results

3.1. Spatio-temporal Distribution of Glacial Lakes (1989-2019)

From 1989 to 2019, the evolution and development of glacial lakes in the Astore Drainage Basin was extremely complicated with the depletion of some lakes, the emergence of new ones, and the growth of existing glacial lakes. Between 1989 and 2019, the number and size of glacial lakes changed dramatically. The Astore Drainage Basin had 120 glacial lakes in 1989. In 1999, there were 126 lakes in the inventory. According to Landsat imagery, the number of glacial lakes increased from 127 in 2009 to 128 in 2019. Over the investigated period, the volumetric and areal extents of the lakes also grew with the growing number. The lakes' total area grew from 4.75 km^2 to 5.86 km^2, and their approximate volume increased from 2043463.17 m^3 to 2522083.32 m^3. The specifics can be found in the Table 1.

Table 1. Areal and volumetric extents of the lakes

	Areal Extent (Km^2)			Volumetric Extent (m^3)		
Year	Glacial-fed Lakes	Non-glacial-fed Lakes	Total	Glacial-fed Lakes	Non-glacial fed Lakes	Total
1989	1.93	2.82	4.75	830241.01	1213222.16	2043463.17
1999	2.282	3.175	5.457	982004.21	1366495.78	2348499.99
2009	2.278	3.298	5.576	980046.56	1419182.01	2399228.57
2019	2.491	3.370	5.861	1071887.82	1450195.50	2522083.32

3.2. GLOF Susceptibility Mapping

To create a single GLOF susceptibility map, the weighted causative factors were combined using the Weighted Sum tool in ArcMap 10.5. In the process, the net weight was used for weighting. The susceptibility to GLOFs is based on the measured weights for each parameter and its respective groups which divides the entire region into different zones. Based on the outburst weightage ranking, it was reclassified into six susceptibility zones: free susceptibility zone, very low susceptibility zone, low susceptibility zone, moderate susceptibility zone, high susceptibility zone and very high susceptibility zone.

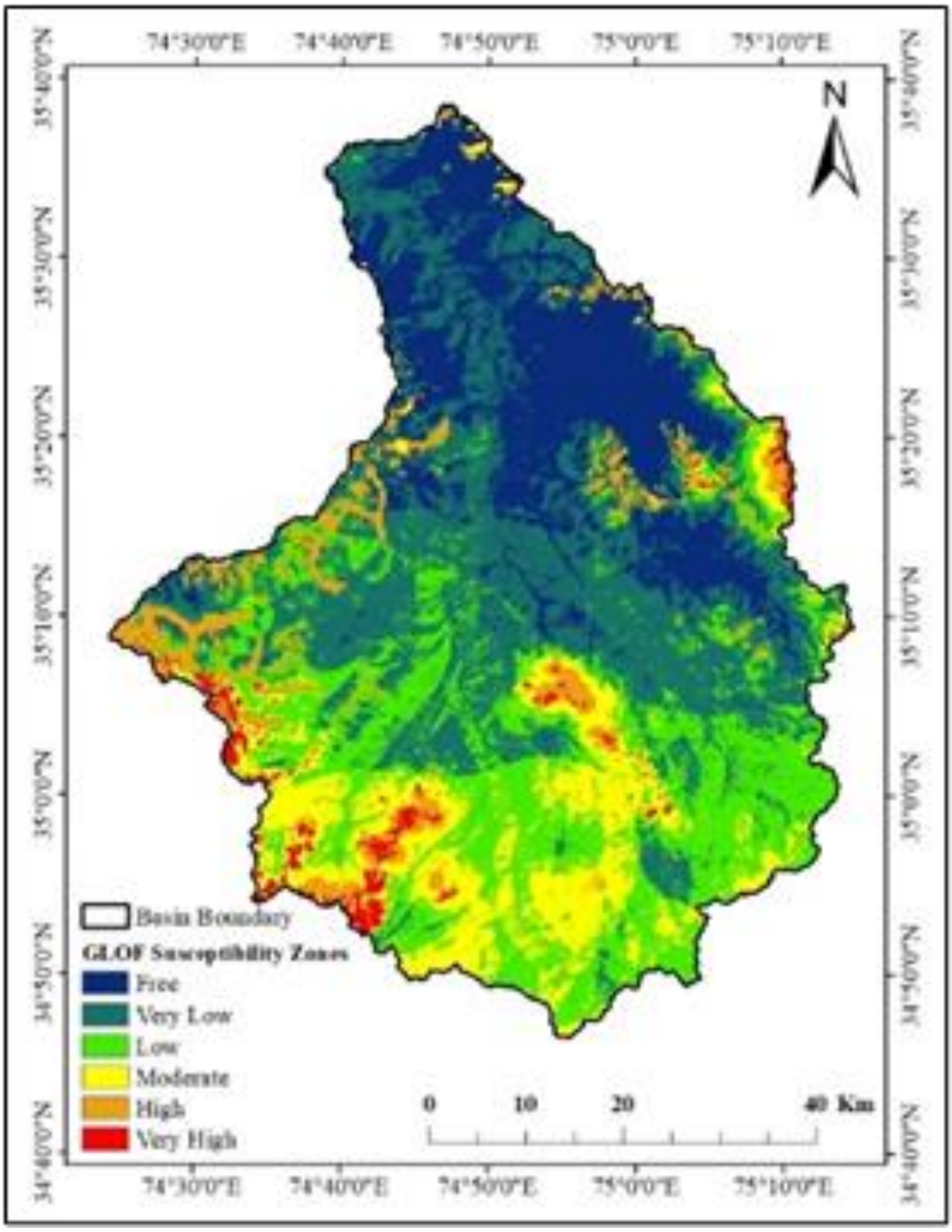

Figure 1. GLOF susceptibility map of Astore Drainage Basin

4. Discussion

From 2009 to 2019, the area of the glacial lakes expanded at a faster pace than the rest of the decades/years. Glacial-fed lakes have grown by 29.07 percent in the last 30 years from 1.93 km² in 1989 to 2.491 km² in 2019 which is considerably more than non-glacial-fed lakes which have grown by just 19.50 percent (from 2.82 km² in 1989 to 3.370 km² in 2019). Furthermore, the findings revealed that smaller lakes grew in size faster than larger lakes. According to the findings of all inventories, there is a strong correlation between elevation and the number of glacial-fed lakes, i.e., the higher the number of glacially fed lakes, the higher the elevation. The finding is not surprising since it is commonly assumed that the ponds left by Quaternary glaciers where non-glacier-fed lakes are found, are at a lower elevation than the current glacier termini where Glacier-fed lakes are found (Wang et al., 2015).

During the study period two lakes in the basin are vanished and 10 glacial lakes have appeared. Out of these ten lakes two of them are non-glacial while the others are Glacial-fed lakes. Non-glacial-fed lakes, as it is well known, are typically created in the ponds left by Quaternary glaciers. Two non-glacial-fed lakes are shown to have formed after 1989 in this study. This may be due to rainwater runoff or significant amounts of snow melting. GLOF susceptibility varies from high to very high in the Southwestern and some Eastern parts of the basin. The Southern part of the study area shows a broad distribution of moderate GLOF susceptible zones. Whereas, GLOF susceptibility varies between, low to very low in Northern and in central part of the basin. According to the results, more than 8.134 percent

(318.4337 km^2) of the basin area is occupied by high and very high susceptibility zones.

5. Conclusion

Glacier retreat results in the formation of glacial lakes. There are various forms of glacial lakes, each of which poses a serious threat to downstream communities and property. The GLOF susceptibility in the Astore Drainage Basin was assessed using the Analytical Hierarchy Process. To achieve the objective, glacial lakes inventory map of 108 lakes with an area greater than 0.01 km^2 was developed. The lakes' locations were verified using high-resolution Google Earth maps. A total of twelve GLOF influencing factors were chosen and organized in a hierarchical order. The weights of each class and class's subclasses were determined. Using Saaty's scale (1977), the CI and CR were estimated. Finally, using the Weighted Sum tool in ArcMap 10.5, the GLOF susceptibility zones were identified, ranging from free to very high. The findings revealed that high and very high zones cover more than 8.134 percent (318.4337 km^2) of the basin area while low and very low zones cover 57.916 percent (2,267.822 km^2). This study's GLOF susceptibility map is a useful guide for disaster risk reduction administrators, policymakers, and planners. They will be able to make quick decisions to reduce the losses and harm caused by current and future GLOFs. To avoid the extremely vulnerable areas, appropriate mitigation techniques and preventive measures can be implemented.

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