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Glacial Lake Outburst Floods: A Review of Events, Causes, and Impact

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Abstract. The occurrences of disastrous Glacial Lake Outburst Flood (GLOF) events have increased dramatically in recent years in response to climate change. Such events are highly complex and volatile flow phenomenon, which triggers suddenly and pose great risk to lives and infrastructure in the susceptible areas. Himalayan region is one of the most vulnerable regions to GLOF events as the extent of glacial retreat has greatly increased due to increasing temperature and significantly impacted the volume and bathymetry of the Glacial Lakes. In order to reduce the after-effects of such events, it is vital to understand the causes, triggering factors, and impacts of the reported GLOF events. The present paper intends to achieve this objective by inventorying the details of the reported GLOF events, exploring the remote sensing tools and numerical modelling methodologies used for detecting and investigating these events, and discussing the predictive dam-breach models reported in the literature. The outcome of this study will also aid in understanding the effects of climate change on the young and fragile Himalayan region.

Keywords: GLOF; Glacial Lakes; Remote Sensing; Numerical Modelling; Moraine-Dam Breach; Review

1 Introduction:

Glaciers are formed by accumulation of snow at higher altitudes where the average temperature lies in the freezing zone. As the accumulation increases, deeply buried snowflakes get tightly packed and crystallized, resulting in glacial ice formation. As the average global temperature has increased due to heightened anthropogenic activities, the glaciers have receded significantly, resulting in formation of a greater number of moraine-impounded glacier lakes (Raj, 2010 [20]; Shrestha et al, 2010 [3]; Schneider et al, 2014 [11]; Liu et al, 2014 [18]). The surface area and the depth of these glacial lakes are growing as a result of glacial retreat, raising the possibility of breaching of moraine dams. Breaching of these dams can further be triggered by extreme precipitation, permafrost deterioration, and dead-ice melting (Lamsal et al, 2016 [9]). This will result in instant release of large quantities of sediment-laden glacial water that can ignite vast damage to the downstream parts of the dams. These events, known as Glacial Lake Outburst Floods (GLOFs), can get aggravated if erodible materials are present (Jha et al, 2016 [22]). Due to its high velocity, continued entrainment of sediment in its flow path, and tendency to flow along existing river channels for very long run out distances, these debris floods/flow events pose significant threat to the lives and property located along its flow channel (Jha et al, 2016 [22]).

In India, the Kedarnath disaster in 2013 (Rao et al, 2014 [21]), and the Chamoli disaster in 2021 (Jha et al, 2016 [22]), caused by cloud outbursts and ice/rock avalanches, respectively, claimed thousands of lives and caused substantial socio-economic losses. Two series of occurrences struck Kedarnath in 2013: the first resulted in landslides, breaching, blockades, flooding, and failures of river banks; the second was outburst flooding in Chorabari Tal Lake in conjunction with erosion of the terrain and concomitant landslides. In the Chamoli Disaster in 2021, a significant amount of rubble blocks fell into the glacial pocket, forcing the lake to burst. This event had endangered lives and inflicted significant financial losses. Nie et al., 2018 [28] inventoried and studied over 60 GLOF events in the Himalayan region alone, and reported the estimated losses to be over hundreds of billion dollars. Thus, implementation of adequate mitigation measures and land-use and development plans is vital while developing infrastructure in the mountainous regions.

This paper aims to inventory the reported GLOF events, regarding their causes, the methodologies employed for their study, and predictive dam-breach models reported in the literature. The outcome of this study will aid in consolidating the knowledge developed regarding the effect of climate change, especially on the young and fragile Himalayan region.

2 Glacial lakes and GLOFs

Classification of Glacial Lakes into different categories plays a vital role in understanding their origin and evolution. However, there is presently no globally-accepted classification system for glacial lakes. Numerous researchers assigned classifications to the glacial lakes in accordance with their knowledge of the region's morphology. In 2018, ICIMOD [4] classified glacial lakes in four groups and seven sub-groups, as shown in Table 1.

An attempt has also been made to summarize the reported cases of moraine-impounded glacial lakes with the objective of understanding the causes of their formation and to study the areas likely to be affected if failure occurs. This summary is given in Table 2. Table 2 further summarizes the volume, depth, and peak discharge of the lakes, probable triggering factors, and methodologies employed to analyze the probability of the GLOF events.

Table 1: ICIMOD Classification of Glacial Lakes (ICIMOD, 2020) [4]

Sl. No.	**Glacial Lake Type**		**Description**
1	Moraine Dammed Lake (M)	End Moraine Dammed Lake	The lake’s water usually touches the walls of the side moraines, but the water is held back by the end moraine (dam), but not necessarily, in contact with the glacier, and may have glacier ice at the lake bottom.
2		Lateral Moraine Dammed Lake	Lake formed in the tributary valley, trunk valley, or between the lateral moraine and the valley wall, or at the junction of two moraines. Lake is held back by the outside wall of a lateral moraine.
3		Other Moraine Dammed Lake	Lake dammed by other moraines (include kettle lakes and thermokarst lakes)
4	Ice Dammed Lake (I)	Supra Glacial Lake	Body of water (ponds or lakes) on the surface of a glacier
5		Dammed by tributary-valley glacier	Lake dammed by glacier ice with no lateral moraines. Can be at the side of a glacier between the glacier’s margin and valley wall
6	Bedrock dammed Lake (B)	Cirque Lake –	A small pond occupying a cirque
7		Other Glacier Erosion Lake	Body of water occupying depressions formed by glacial erosion. These are usually located on the mid-slope of hills, but not necessarily in a cirque
8	Other dammed Lakes		Lakes formed in a glaciated valley and fed by glacier melt, but the damming material is not directly part of the glacial process, for example, debris flow, alluvial, or landslide-blocked lakes

Table 2: Summary of reported Causes, Methodology and Parameters taken for consideration for the analysis of Glacial Lake

Sl. No.	**Events**	**Area**	**Triggering Factors**	**Tools**	**Methodology**	**Volume of Lake (million m^3)**	**Lake Average Depth (meters)**	**Peak Discharge (cumecs)**	**References**
1	Glacial lake (33° 09′ 32.56″ N & 76° 59′ 05.38″ E)	Zanskar Basin, J&K, India	Collapse of Unstable Natural Dams	Topographical Maps in early days. Replaced by Remote Sensing using MSS, TM, LISS III, ASTER DEM	Monitoring of extent of glacial lake is observed	4.2	10	1.7-196	Raj, 2010 [20]
2	Glacial Lake L2	Dhauliganga River Basin, Pithoragarh Distt, Uttarakhand	Lake Area Expansion, Dead Ice Melting, Seepage, Seismic Activity	HEC-RAS (Hydrologic Engineering Centre's River Analysis System)	Analysis of the Glacial Lake using Numerical Modelling	2	30	4272	Jha et al, 2016 [22]
3	Lumi Chimi Lake	Sun-Koshi Basin, Transboundary between Tibet (China) & Nepal	Retreat of Glaciers	Dambreak and Hydrodynamic Modelling	Risk Assessment of the event before it occurs	307.2	80	5040-8380	Shrestha et al, 2010 [3]
4	Chamlang South Tsho	Hongu valley, eastern Nepal Himalaya	Lake Area Expansion, Ice Avalanches, Rock falls, Landslides	Observational Data, Photographs, Ground-based Surveys, Field and Remote Sensing data	GLOF Hazards, Bathymetry, Surrounding Material decides the vulnerability	34.9-35.6	40.2	Not Available	Lamsal et al, 2016 [9]
5	Franz Joseph Glacier	New Zealand, Westland Tai Poutini National Park	Formation of BlackHole due to collapse of ice	Visual Representation Data was utilized	Sub-Glacial Channel shifted to Supra-Glacial Position due to Ice Collapse and Outburst Flooding	Not Available	25	Not Available	Goodsell et al, 2005 [6]

Sl. No.	Events	Area	Triggering Factors	Tools	Methodology	Volume of Lake (million m^3)	Lake Average Depth (meters)	Peak Discharge (cumecs)	References
6	Lemthang Tsho	Gasa District, North-western Bhutan	Earthquake, Rainfall, Draining of Supraglacial Pond	Satellite images, Field observation and Remote Sensing data	Four Bridges Washed away, Agricultural Land Affected and Estimated loss 0.976 Nu. Million	0.37	6.29	1198	Gurung et al, 2017 [10]
7	Guangxieco Lake	Bomê County, South-eastern Tibet (China)	Climatic Observations - Temperature and Rainfall, Material Composition of Dam	Satellite Images, Field Investigation and Past Studies	Five People Died, 51 Houses swept ayaw, 18 Bridges Washed away and Economic Loss more than CNY 100 million	0.97	14.1	1270	Liu et al, 2014 [18]
8	Teesta basin	Sikkim	Lake Area Expansion, Ice Avalanches	Satellite Data, Images from Landsat and Indian Remote Sensing, MIKE-11 Dam Break Model	Analysis of the Potential Dangerous Lake Using MIKE-11 Dam Break Model	42.93	37	2611.136	Aggarwal et al, 2013 [1]
9	Shishper Glacier lake	Gilgit-Baltistan, Pakistan	Blockage of Melt Water Originating from Mochuwar Glacier	Images from Landsat and Sentineal, Global Digital Elevation Model (GDEM), ArcMap 10.5	More than 2000 People are Prone to Flood, Karakoram Highway Damaged	8	21	4500	Khan et al, 2021 [15]
10	Lake 513	Carhuaz, Peru	Rock-Ice Avalanche	Remote Sensing Images, Digital Elevation data, RAMMS and IBER model - Numerical and Physically based avalanche & debris flow	Santa Valley Highway affected, Several Bridges swept away and Agricultural Land affected	0.2-0.4	Not Available	9000-40000	Schneider et al, 2014 [11]

2.1 Methodologies

2.1.1. Remote Sensing Tools

In conventional times, data was collected from the topographic maps available by reputed agencies to identify the aerial extent of the glacial lake. With the increase in advancement of technology, various remote sensing (RS) techniques such as Multispectral Scanner (MSS) (Raj, 2010 [20]), Linear Imaging Self Scanning (LISS) (Aggarwal to al, 2016 [1]) satellite data, and Thematic Mapper (TM) (Raj, 2010 [20]) tools are used, provided a minimum cover of snow and cloud is present in the sites. Data Elevation Models (DEMs) such as SRTM (Shrestha et al, 2010 [3]) and ASTER (Lamsal et al, 2016 [9]) are also used to recreate the digital elevation models of the sites and conduct in-depth studies of the concerned areas.

In Zanskar Basin (Raj, 2010 [20]), the conventional methodology of using topographic maps are utilised in conjunction with remote sensing methodologies like Multi-Spectral Scanner, Linear Imaging Self Scanning, Advanced Spaceborne Thermal Emission & Reflection Radiometer to determine the characteristics of the glacial lakes. In Chamlang Lake Tsho (Lamsal et al, 2016 [9]), images obtained from RS tools and photogrammetric techniques, and field-based methodologies, like Sonar-Sounding Machine, GPS, and fishing line method were utilized to study the area. Figure 1 depicts the various steps involved in processing the data to recreate the profile of the glacial lakes.

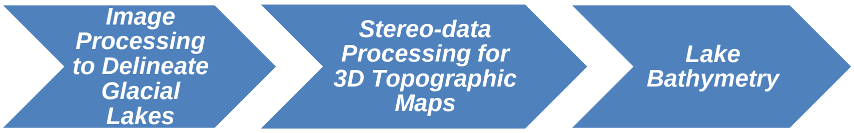

Figure 1. Steps involved for the Interpretation for the Data

2.1.2 Numerical Modelling

For the study of glacial lakes, empirical formulations and numerical modeling are often used. One of the widely used numerical tool is Hydrologic Engineering Centre's River Analysis System (HEC-RAS) (Jha et al, 2016 [22]). This tool simulates GLOF phenomenon from the source to the downstream flow path locations. Using the model, cross-sectional measurements of the main river section at regular intervals can be determined, and the same can be utilized for routing floods. Hydrographs can be generated along different sections of the flow channel which can be further used to estimate the peak discharge intensity (Shrestha et al, 2010 [3] & Jha et al, 2016 [22]). However, there are some limitations of this model, one of which is its inability to consider debris and sediment-laden water in the simulations. In the study on the Dhauliganga Basin (Jha et al, 2016 [22]), HEC-RAS was used to create the glacial lake representation. HEC-RAS was also used to generate the Hydrological model for the Mandakini River (Rao et al, 2014 [21])

2.2 Empirical equations for discharge estimation and stability of moraine dams

The simplest and fastest methods for determining the various parameters required for vulnerability assessment of moraine dams are empirical relationships. Empirical relationships, on the other hand, do not incorporate fundamental rules of fluid mechanics and hydraulics as they are derived through statistical study of historical events. Various researchers have proposed empirical equations to determine peak discharge values based on estimated average breach width and time of failure in moraine dams (Liu et al, 2014 [18]).

Peak discharge is an important consideration for the assessment because it helps to visualize the size of the flood downstream. The findings of the multiple regression analysis showed that compared to other factors like embankment width & embankment length (E_l), empirical relationships with parameters like volume of water (V_w) & height of water (H_w) gave more precise forecasts of maximum flow discharge (Q_{max}) (Bajracharya et al, 2015 [32]). The models that predict peak outflow using only H_w & V_w don't considerably benefit from the addition of E_l & Q_{max} to the relationship, making H_w & V_w more significant features to define peak discharge compared to other parameters. Table 3 shows the summary of the empirical relationships developed by various researchers.

Table 3: Summary of Empirical Relationships

Sl. No.	**Parameter**	**Lake Volume (m^3)****	**References**
1	**Lake Volume (m^3)**	$V = 0.104A^{1.42}$	Huggel et al, 2002 [17]
2		$V = 0.035A^{1.5}$	
3		$V = 0.104A^{1.42}$	Evans, 1986 [12]
4		$V = A * MD$	Wang et al, 2012b [35]
5	**Lake Depth (m)**	$D = 0.104A^{0.42}$	Huggel et al, 2002 [17]
6		$MD = 4A * 10^{-5} + 5.0564$	Wang et al, 2012b [35]
7		$D = 0.087A^{0.434}$	Patel et al, 2017 [29]
8	**Average Breach Width (m)**	$B = 0.1803V_W^{0.32}h_b^{0.19}$	Froehlich 1987 [14]
9	**Time of Failure (hr)**	$t_f = 0.00254V_W^{0.53}h_b^{-0.90}$	
10	**Peak Discharge (m^3s^{-1})**	$Q_{max} = 75V^{0.67}$	Clague & Mathews, 1973 [7]
11		$Q_{max} = 0.72V^{0.53}$	Evans, 1986 [12]
12		$Q_{max} = 0.0048V^{0.896}$	Popov, 1991 [30]
13		$Q_{max} = 0.00077V^{1.017}$	Huggel et al, 2002 [17]
14		$Q_{max} = 1.165\left(\frac{L}{B}\right)^{\frac{1}{10}}(\frac{B}{b})^{\frac{1}{3}}b(H-h)^{\frac{3}{2}}$	Lue et al, 1999 [24]
15		$Q_{max} = 0.00013(PE)^{0.60}$	Huggel et al, 2002 [17]
16		$Q_{max} = \frac{2V}{T_w}$	Huggel et al, 2002 [17]; Popov, 1991 [30], and Haeberli 1983 [16]

**where V is the volume of glacier lake; A is an area of Glacier Lake in m^2; MD is the average depth of Glacial Lake in m; V_w = reservoir volume in m^3; h_b is the height of water above breach invert level; L is the lake's length (m), B is the breach's maximum width (m), b is its avg width (m), H is the lake's maximum depth (m), and h is height of remaining dam (m)

3 Estimation of Peak Discharge of Reported Cases

Table 4: Summary of Physical Information about Glacial Lakes including average breach width and time of failure

Sl. No	Lake	Area (m^2, $\times 10^6$)	Volume (m^3, $\times 10^6$)	Mean depth (m)	Type of lake	Average Breach Width $B = 0.1803*1.4*V_W$^0.32 h_b^0.19	Time of Failure $t_f=0.00254V_W$^0.53 h_b^(-0.90)	Discharge: Glacier, Tunnel Events: Clague and Mathews 1973 [7] $Q_{max} = 75(V/10^6)^{0.67}$	Discharge: Glacier, Tunnel Events: Walder and Costa 1996 [34] $Q_{max} = 46(V/10^6)^{0.66}$	Discharge: Glacier, NonTunnel Events: Haeberli 1983 [16] $Q_{max} = 2V/t_w$ where t_w=1000s	Discharge: Glacier, NonTunnel Events: Walder and Costa 1996 [34] $Q_{max} = 1100(V/10^6)^{0.44}$	Discharge: Moraines: Popov 1991 [30] $Q_{max} = 0.0048V^{0.896}$	Discharge: Earth- and rock-fill: Evans 1986 [12] $Q_{max} = 0.72V^{0.53}$	Reference
1	**Ice Cave Lake**	0.0035	0.01	2.9	Ice-dammed	5.9	0.1	3.43	2.2	20	145.01	18.42	94.91	Maag 1963 [25]
2	**Gruben Lake 5**	0.01	0.05	5	Thermo-karst	10.9	0.2	10.08	6.37	100	294.4	77.9	222.73	Teysseire 1999 [7]
3	**Crusoe-Baby Lake**	0.017	0.08	4.7	Ice-dammed	12.6	0.3	13.81	8.69	160	362.04	118.69	285.74	Maag 1963 [25]
4	**Gruben Lake 3**	0.021	0.15	7.1	Ice-dammed	16.6	0.2	21.04	13.15	300	477.39	208.46	398.71	Kääb 1996 [19]
5	**Gruben Lake 1**	0.023	0.24	10.4	Moraine-dammed	20.8	0.2	28.83	17.93	480	587.06	317.62	511.5	Kääb 1996 [19]

Sl. No	Lake	Area (m^2, $\times 10^6$)	Volume (m^3, $\times 10^6$)	Mean depth (m)	Type of lake	Average Breach Width $B = 0.1803*1.4*V_W$^0.32 h_b^0.19	Time of Failure $t_f=0.00254V_W$ ^0.53 h_b^(-0.90)	Discharge						Reference
								Glacier, Tunnel Events		Glacier, NonTunnel Events		Moraines	Earth- and rock-fill	
								Clague and Mathews 1973 [7]	Walder and Costa 1996 [34]	Haeberli 1983 [16]	Walder and Costa 1996 [34]	Popov 1991 [30]	Evans 1986 [12]	
								$Q_{max} = 75(V/10^6)^{0.67}$	$Q_{max} = 46(V/10^6)^{0.66}$	$Q_{max} = 2V/t_w$ where t_w=1000s	$Q_{max} = 1100(V/10^6)^{0.44}$	$Q_{max} = 0.0048V^{0.896}$	$Q_{max} = 0.72V^{0.53}$	
6	**MT' Lake**	0.0416	0.5	12	Ice-dammed	27	0.3	47.14	29.11	1000	810.85	613.08	754.72	Blown and Church 1985 [5]
7	**Lac d'Arsine**	0.059	0.8	13.6	Moraine-dammed	32.1	0.3	64.58	39.7	1600	997.13	934.14	968.21	Vallon 1989 [33]
8	**Nostetuko lake**	0.2622	7.5	28.6	Moraine-dammed	75.7	0.5	289.3	173.9	15000	2669.44	6938.99	3170.41	Clague and Evans 1994 [13]
9	**Between Lake**	0.4	7.5	18.8	Ice-dammed	69.9	0.8	289.3	173.9	15000	2669.44	6938.99	3170.41	Maag 1963 [25]
10	**Abmachimai Co**	0.565	19.4	34.3	Moraine-dammed	106.2	0.8	546.88	325.62	38800	4055.32	16259.66	5246.47	Meon and Schwarz 1993 [27]

Sl. No	Lake	Area (m^2, $\times 10^6$)	Volume (m^3, $\times 10^6$)	Mean depth (m)	Type of lake	Average Breach Width B = 0.1803*1.4*V_W^0.32 h_b^0.19	Time of Failure t_f=0.00254V_W^0.53 h_b^(-0.90)	Discharge						Reference
								Glacier, Tunnel Events		Glacier, NonTunnel Events		Moraines	Earth- and rock-fill	
								Clague and Mathews 1973 [7]	Walder and Costa 1996 [34]	Haeberli 1983 [16]	Walder and Costa 1996 [34]	Popov 1991 [30]	Evans 1986 [12]	
								$Q_{max} = 75(V/10^6)^{0.67}$	$Q_{max} = 46(V/10^6)^{0.66}$	$Q_{max} = 2V/t_w$ where tw=1000s	$Q_{max} = 1100(V/10^6)^{0.44}$	$Q_{max} = 0.0048V^{0.896}$	$Q_{max} = 0.72V^{0.53}$	
11	**Gjanupsvatn**	0.6	20	33.3	Ice-dammed	106.6	0.8	558.15	332.23	40000	4110.04	16709.53	5331.86	Costa and Schuster 1988 [8]
12	**Quongzonk Co**	0.753	21	27.9	Moraine-dammed	104.7	1	576.7	343.1	42000	4199.23	17456.2	5471.53	Meon and Schwarz 1993 [27]
13	**Laguna Parón**	1.6	75	46.9	Moraine-dammed	173.6	1.2	1353.17	794.87	150000	7352.24	54613.01	10742.74	Lliboutry et al. 1977 [23]
14	**Summit Lake**	5	250	50	Ice-dammed	258.4	2.1	3031.66	1759.54	500000	12487.81	160618.47	20334.84	Mathews and Clague 1993 [26]
15	**Phantom Lake**	6	500	83.3	Ice-dammed	355.4	1.9	4823.6	2780.21	1000000	16941.02	298894.8	29362.07	Maag 1963 [25]

Using the empirical relationships mentioned in Table 3, the average breach width B, time of failure t_f, and peak discharge values for 15 different cases of moraine dam is estimated and tabulated in Table 4. The results showed that when the glacial lake's volumetric capacity increases, the peak discharge of the lake also consistently rises. However, it has been observed that the average breach width, B, and time of failure, t_f, change in proportion to the mean bathymetric depth, as shown in Table 5.

Table 5: Parametric effect of the Breach Depth and Volume Released

Sl. No.	**GLOF Scenarios**	**Breach Depth (h_b)**	**Volume Released (10^6 x m^3)**	**Average Breach Width B = 0.1803*1.4*V_W^0.32 h_b^0.19**	**Time of Failure t_f=0.00254V_W^0.53 h_b^(-0.90)**
1	Scenario 1	60	4.34	73.10	0.21
2	Scenario 2	30	2.17	51.30	0.27
3	Scenario 3	15	1.08	36.00	0.35

For the Safed glacial lake located in Goriganga Basin, Uttrakhand, India (Sattar et al, 2020 [2]), Table 5 shows the parametric effect of the Breach Depth and Volume Released on the Average Breach Width and Time of the Failure. When the breach depth is reduced to half, as in Scenario 2, it is shown that the breach breadth decreases by 30%. The average breach width further decreases by 30% if the drop continues to 15 meters, as shown in Scenario 2. When the time of failure is taken into account, it can be seen that the moraine dam's failure time increases by 29% and 30% in comparison to scenarios 1 and 2, respectively; based on the equations proposed by Froehlich, 1995 (Aggarwal et al, 2016 [1]). This shows that the time of failure is directly connected to volume released but indirectly related to breach width, whereas the breach width is directly related to volume released but indirectly related to breach depth. Due to the inverse relationship between Average breach width and Time of failure, the breach depth has a significantly more noticeable effect even when the effect of volume released is assumed to be the same in all circumstances.

4 Concluding Remarks

The high-altitude glaciers have suffered greatly as a result of extensive anthropogenic-activities led climate change. In areas where glacial lakes are growing in lateral extent and bathymetry, increasing possibility of higher peak discharges and GLOFs are risking the lives of the local inhabitants, local flora, fauna, and other infrastructure.

In this paper, reported studies on glacial lakes are examined in order to ascertain their formational behavior, its after-effects, and potential corrective actions. The approaches that are utilized globally to anticipate the size of these glaciers include remote sensing and numerical simulation utilizing HEC-RAS. These lakes have been categorized by ICIMOD based on the failure behavior that is anticipated to occur in the future. In order to predict the peak discharge, breach width, and time of failure of various structures that result in the abrupt discharge of enormous amounts of water in the downstream region, numerous empirical equations have been developed and reviewed in this paper. The established empirical relationships are then used to estimate the average breach width, B, time of failure, t_f, and peak discharge for 15 identified cases of glacial lakes.

The peak discharge values aids in identifying the glacial lake's susceptibility in the downstream sections of the impacted area. The results show that as the depth of the breach grows, so does the likelihood of failure. If the breach depth is reduced by 50%, the time of failure increases by 28–29% and the average breach width drops by about 30%.

Reviewing all the various glacial lakes enables us to spot certain significant problems that, if resolved, can reduce the impact of GLOF to some level: (a) Quantification of the climatic conditions in space-time and further determination of projections for the future, (b) Establishment of a database that compiles data on glacier surface areas and their pace of retreat across time, (c) Development of an algorithm that aids in projecting the size of lakes based on present-day spatial features, (d) Development of hydrological models that account for potential changes in the regional availability of water.

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