https://doi.org/10.5194/egusphere-2025-4136
Preprint. Discussion started: 13 October 2025

Brief communication: Towards defining the worst-case breach scenarios and potential flood volumes for moraine-dammed lake outbursts

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Abstract. Moraine dam failures are the main source of catastrophic glacial lake outburst floods (GLOFs). The effective GLOF disaster risk management requires reliable identification of areas at risk. While predictive outburst flood modelling benefits from advancing tools and computational capacities, some of the fundamental considerations remain poorly addressed. Among them, the outburst flood scenarios are essential yet often oversimplified input for modelling. Here we present novel methodology which enables the estimation of a maximum breach depth and so the calculation of potential flood volume (PFV), with the key parameter being the slope of the breached channel (α) derived from past events.

1 Introduction

Catastrophic outbursts of moraine-dammed lakes are the major concern in high mountain regions across the globe (Emmer, 2024). The effective GLOF disaster risk management calls for the identification of GLOF hazard zones, which is typically achieved through predictive GLOF modelling which – among other inputs – requires lake volume estimates and potential flood volume scenarios. While methodologies for the estimation of a glacial lake volume progressed substantially in recent years (e.g., Bazai et al., 2024; Gantayat et al., 2024; Qi et al., 2025), the way how the PFV scenarios are defined often neglects elementary parameters including moraine dam geometry or tend to exclude dams which do not meet given distal face slope steepness threshold (e.g., Fujita et al., 2013). The tendency to disregard moraine dam geometry when defining GLOF scenarios is observed even in otherwise state-of-the-art GLOF risk assessment studies (e.g., Furian and Sauter, 2025).

At the same time, the systematic analysis of past GLOFs suggest that large moraine-dammed lakes typically do not drain completely during the GLOF and that the breached channels are typically not flat (e.g., Emmer et al., 2022; Lützow et al., 2023). As a result, the breach scenarios that do not take into account moraine dam geometry may be overestimated and the worst-case scenarios (WCS) assuming complete lake drainage may be unrealistic in certain dam geometry / bedrock overdeepening settings. This short comment aims at presenting a simple method for the estimation of a maximum breach depth and so the calculation of the PFV of the WCS, building on the quantitative analysis of post-GLOF geometries of outflow channels through breached moraine dams.

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2 Data and Methods

Using the most updated version (v 4.1) of the global GLOF database (Lützow et al., 2023) available from glofs.geoecology.uni-potsdam.de as well as regional databases and source papers (see Supplement I), we searched for and compiled the list of relevant GLOF events which met following criteria:

- **lake dam type:** moraine (all other lake dam types as well as not classified dams were not considered)
- **outburst mechanism:** moraine dam breach (overtopping, piping, tunneling and other specific mechanisms were excluded)
- **outburst volume:** 1,000,000 m^3 or more (small events and events with unknown outburst volume were excluded)
- **available data and other considerations:** only cases with available post-GLOF DEM were considered; cases where the breached channel could not be localized in remote sensing images were removed; cases with major anthropogenic modification of a breached channel were removed

Our final list of relevant events composes of 24 GLOFs meeting the criteria (see Supplement I). Out of these, 14 (58.3%) are located in High Mountain Asia, followed by 7 cases from the Andes (29.2%; including tropical (n=5) as well as Patagonian (n=2)) and remaining 3 cases (12.5%) from Canadian Coast Mountains.

The post-GLOF lake level elevation ($z_{lake\_postGLOF}$) and elevation of the stream at the toe of the breached moraine dam ($z_{toe\_postGLOF}$) were measured in QIS using 12.5 m Advanced Land Observing Satellite Digital Elevation Model (ALOS PALSAR DEM available from NASA Earthdata platform) for which the data were acquired between 2008 and 2011, Canadian Digital Elevation Model (CDEM) or 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model hosted by Google Earth (https://earth.google.com/). In addition, the length of the breached channel (d) was measured between the lake and the toe of the breached moraine dam (see Fig. 1) from high resolution ESRI and Google satellite images connected to QGIS as XYZ tiles. The post-GLOF mean slope steepness of the breached channel (α) was then calculated using basic trigonometric function:

$$\alpha = \sin^{-1}((z_{lake\_postGLOF} - z_{toe\_postGLOF})/d) \quad (1)$$

where α is the mean slope of the breached channel (in °), $z_{lake\_postGLOF}$ is the elevation of post-GLOF lake water level (m asl), $z_{toe\_postGLOF}$ is the elevation of the toe of the breached moraine dam (in m asl) and d is the length of the breached channel (in m). The list of analyzed GLOFs with their characteristics is presented in Suplement 1.

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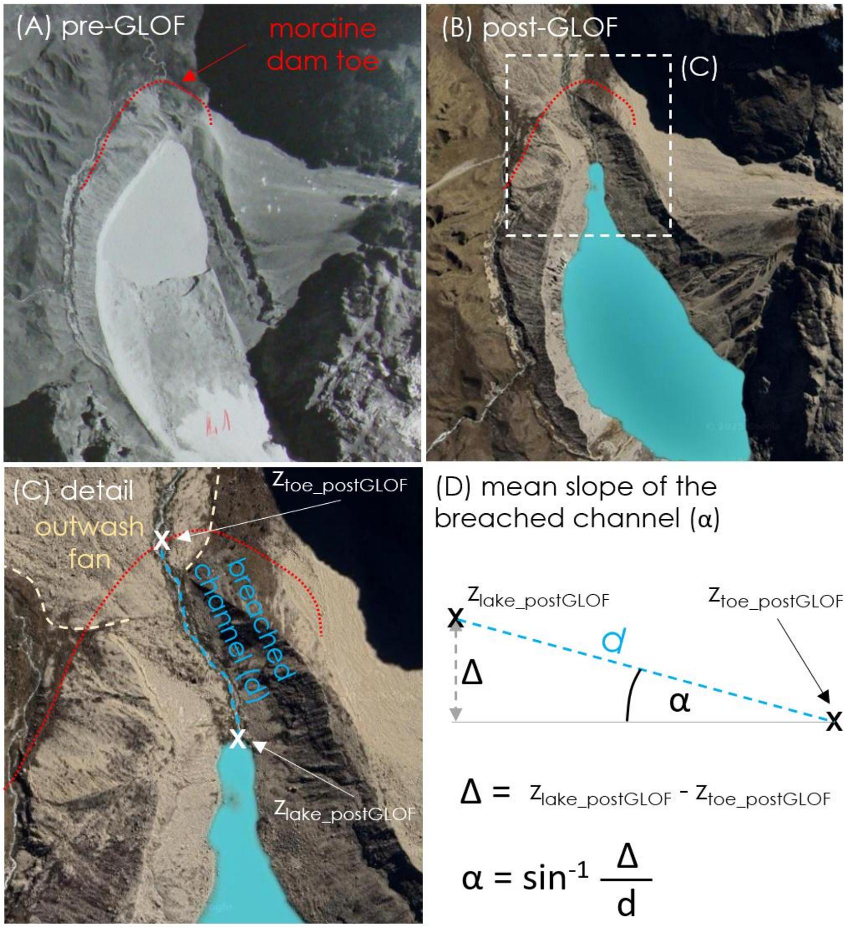

Figure 1: Methodology used for the estimation of the mean slope of the breached channel (α) exemplified by Jancarurish lake, Cordillera Blanca, Peru, which experienced and outburst in 1950. (A) shows the situation before the outburst with delineated toe of moraine dam; (B) shows post-GLOF image of the same area; (C) shows detail of breached moraine dam and (D) shows the methodology of calculating the mean slope of the breached channel. Background images: (A) a segment of an aerial image from the archive of Autoridad Nacional del Agua (ANA) in Huaraz, Peru; (B) and (C) ESRI XYZ tile collection (© ESRI).

3 Results

3.1 Observed limits of dam breaching

We found rather narrow range of the mean slope of the breached channels of 24 major GLOFs worldwide (see Supplement II). It ranges from 2.3° (South Lhonak lake; Nostetuko lake) to 19.5° (Zhangzangbo lake) while the median is 5.0° and mean is 5.5°. One half of breached channels (Q1 to Q3) have mean slopes between 3.1° to 6.6°. We also observed regional differences: while the mean and median slope of the breached channels is 5.7°, respectively 4.5°, in HMA, these values are increased to 6.8°, respectively 6.9°, in Peruvian Andes, and decreased to 3.0° in Patagonian Andes. The lowest values of the mean slope of the breached channel are observed in Coastal Mountains with Nostetuko (2.3°) and Queen Bess Lake (2.8°). We found no

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correlation between the flood volume and the mean slope of the breached channel, suggesting that these thresholds of the slope of the breached channel are independent to it and thus applicable to predicting outbursts of different magnitudes. Similarly, there is no correlation between the elevation of the lake and the slope of the breached channel, although the breached channels in lower elevation regions (Patagonia, Coast Mountains) tend to be flatter (lower topographic potential).

3.2 Geometric approximation of maximum breach depth and flood volume

The minimum mean slope of the breached channel (α) derived from past moraine dam failures (Supplement 1) allows for the calculation of maximum breach depth (h_b) and potential flood volume (*PFV*; see Fig. 2). Maximum breach depth (h_b) is calculated as follows:

$$h_b = (z_{lake\_preGLOF}) - (z_{Toe} + d \cdot \sin\alpha) \quad (2)$$

, where h_b is maximum breach depth (max. lake level drop, in m), $z_{lake\_preGLOF}$ is the elevation of the lake water level before the GLOF (m asl); z_{Toe} is the minimum elevation of the moraine toe (in m asl), d is the length of the breached channel measured from the toe of the moraine dam to the lake (in m) and α is the selected value of the mean slope of the breached channel (in °).
Potential flood volume (*PFV*) can then be calculated as follow:

$$PFV = h_b \cdot A \quad (3)$$

where PFA is potential flood volume (in m^3), h_b is maximum breach depth (lake level drop; in m) and A is lake area (in m^2).

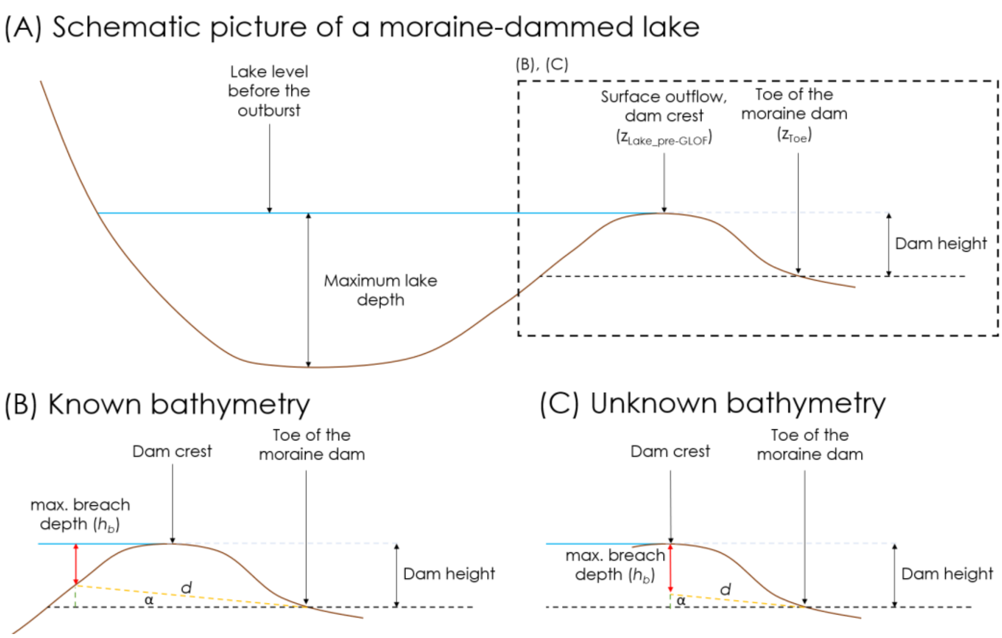

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Figure 2. Estimating max. breach depth of a moraine-dammed lake. (A) shows a schematic picture of a moraine-dammed lake with key terms. (B) shows how maximum breach depth is estimated for lakes with known bathymetry and (C) shows how maximum breach depth is estimated for lakes with unknown bathymetry.

3.3 Potential flood volume and released volume of selected lakes

We compared selected examples of the worst-case glacial lake outburst floods scenarios with revised PFV estimates using presented method (Table 1), revealing that the new method tends to provide rather modest estimates. In general, the difference is higher for lakes with wide dams with gently sloped outflow channels.

Table 1. The comparison of selected worst-case scenario PFV derived from the literature with the estimates obtained with the new method (see Supplement III for the input data).

Examples of worst-case scenarios for lakes that have not yet produced a GLOF			
Lake	Previously estimated potential flood volume (Reference)	Revised worst-case scenario PFV using α=3° (this study)	% (revised PFV to the previous estimate)
Galong Co, China	$469.0 \cdot 10^6$ m^3 (Yang et al., 2023)	$125.3 \cdot 10^6$ m^3	26.7%
Gepang Gath, India	$12.6 \cdot 10^6$ m^3 (Worni et al., 2013)	$4.8 \cdot 10^6$ m^3 (using the same lake area) $6.4 \cdot 10^6$ m^3 (using current lake area)	37.8% 50.5%
Lower Barun, Nepal	$179.0 \cdot 10^6$ m^3 (Sattar et al., 2021)	$90.1 \cdot 10^6$ m^3	50.3%
Lumding, Nepal	$5.2 \cdot 10^6$ m^3 (Fujita et al., 2013)	$4.4 \cdot 10^6$ m^3	85.6%
Thorthormi, Bhutan	$56.4 \cdot 10^6$ m^3 (Osti et al. ,2013)	$33.5 \cdot 10^6$ m^3 (using the same lake area) $79.5 \cdot 10^6$ m^3 (using current lake area)	59.3% 141.0%

4 Discussion and conclusions

4.1 Reconsidering the “worst-case GLOF scenario”

The “worst-case scenario” of a GLOF is frequently defined as 100% of a lake water release (e.g., Allen et al., 2022). However, available literature suggests that a complete moraine-dammed lake emptying due to a GLOF is rather rare process and there are several reasons why moraine dam breaches typically do not lead to complete lake emptying. For instance, Emmer et al., (2022) found that less than 10% of cases experienced a complete lake emptying, all of which were small and rather shallow lakes (where dam height > lake depth). We argue that a complete lake emptying is in many cases not realistic considering often overdeepened nature of glacial lake basins with increasing lake depth towards the glacier, as well as lithological and physical limits of breach development.

Field observations and laboratory studies of overtopping failures in homogeneous embankments (Frank, 2016) show that breach incision typically migrates upstream from the downstream face, lowering the breach invert until it approaches the lowest continuous slope toward the downstream toe (Halso, 2024). This is because once erosion reaches the toe elevation, further vertical incision is constrained by the downstream valley grade, and hydraulic energy is dissipated mainly through lateral widening. Moraine dams, despite their heterogeneous composition, often behave similarly during breaching processes: erosion proceeds retrogressively until it intersects the lowest outlet control, which is frequently at or near the toe. By

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representing the breach channel as a straight slope from the lake margin to the toe, the maximum breach depth (h_b) can be estimated directly from the post-GLOF lake level, the toe elevation, and the channel slope, providing a simple way to derive potential flood volume and, subsequently, peak discharge estimates. This approach assumes that (i) erosion is not arrested prematurely by resistant material (e.g., ice cores, buried boulders, clay beds or bedrock), (ii) the toe elevation (z_{toe}) is correctly identified as the true lowest breach control point, and (iii) there is sufficient hydraulic head and duration for the breach to incise to this level. Where these conditions are not met, h^b should be treated as an upper bound, and site-specific corrections may be needed.

These reasons combined with insights from the past GLOFs, we find complete lake emptying of a large moraine-dammed lake rather unlikely and we offer a simple methodology for designing the worst-case scenario by estimating maximum breach depth (h_b) and PFV.

4.2 Lessons for GLOF modelling: moraine dam geometry and outflow location matter

Predictive GLOF hazard and risk assessments typically rely on scenario-based modeling, where potential outburst events are defined using breach parameters such as breach depth, width, and formation time. In empirically calculated breach, parameters including the breach width and breach formation time are a function of the breach depth (Freohlich 1995). These parameters critically influence the shape and magnitude of the resulting hydrographs, particularly peak discharge and total flood volume. The ~40% reduction in the breach depth can increase time of failure by ~33% and decrease breach width by ~16% (Sattar et al., 2021). However, in the absence of standardized procedure to determine the WCS, these GLOF scenarios are often modeled under the assumption of complete lake drainage.

This approach can significantly overestimate downstream hazard, particularly in cases where the maximum lake depth exceeds the dam height, which is common in large moraine-dammed lakes formed in overdeepened glacial basins. Another key factor influencing GLOF magnitude is the breach location. A breach forming at the lowest point of the moraine toe is more likely to result in a deeper incision and thus a larger volume of water released. This was evident in the 2023 South Lhonak Lake GLOF event, where the breach occurred toward the orographic left of the moraine, rather than at its lowest elevation. This constrained the incision depth and resulted in partial drainage of the lake—approximately 50% of the lake volume remained. If the lake would have had the breach formed at the lowest point of the moraine toe, it is likely that a deeper incision would have occurred, leading to a larger volume of water release in the GLOF event.

In addition, from a modeling perspective, assuming full drainage of a glacial lake can lead to substantial overestimation of key flood parameters such as flow depth, velocity, and inundation extent. Modeling the outflow based on the full lake volume—without considering these physical constraints—can produce unrealistic scenarios that exaggerate downstream hazard. For instance, GLOF arrival time is highly dependent on the breach depth, which significantly influences the flood dynamics and consequently the GLOF lead-time (Sattar et al., 2021). The breach depth governs the rate at which water is released from the lake, with deeper breaches typically resulting in a more rapid outflow, thereby reducing the available

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warning time for downstream areas. Conversely, a shallower breach would generally result in a slower discharge. Thus, accurately quantifying breach depth is crucial for the reliability of GLOF prediction models.

The breach depth is typically limited by the dam height and the topography of the outflow zone and a more realistic estimate of maximum breach depth allows for the development of better-constrained WCS. These observations underscore the importance of carefully defining breach scenarios based not only on breach dimensions, but also on dam geometry and topography as well as outflow (potential breach) location. Accounting for these factors is essential to avoid overestimation of GLOF hazard in scenario-based modeling, particularly for the WCS GLOF assessments.

4.3 Remaining challenges and limitations

While the slope of the breach channel (α) and so the breach depth (h_b) directly control the potential flood volume, they only indirectly control the outburst flood peak discharge – a key characteristics of a flood in hazard zonation and disaster risk assessments. The peak discharge is a function of the timing of breach development (how fast the breach develops) and its cross-profile shape and area (how much water can go through it). Only limited amount of literature addresses these highly uncertain inputs, generally assuming that large (>30 m deep) moraine dam breaches develop within tens of minutes to few hours; i.e., assuming incision rates up to 2 m per minute (Froehlich, 1995; Froehlich, 2025).

The remaining uncertainties related to the proposed method concern primarily two questions:

(i) can breached channels be flattened below the observed thresholds derived from documented cases? Although unlikely, we cannot exclude the possibility of a GLOF magnitude beyond the observations. In such cases, the outflow channel erosion could possibly go beyond the thresholds. Therefore, we recommend not to use proposed method for flood magnitudes exceeding those in the dataset (i.e., flood volumes in magnitude of 108 m3 and peak discharge in magnitude of 104 m3/s).

(ii) can the valley floor material beneath the actual moraine dam be eroded too during a GLOF? Our observation suggests that in moraine-dam breaches, incision rarely continues below the toe of the dam because the toe sets the hydraulic control for lake drainage, and once reached, the flow energy shifts from vertical cutting to lateral widening. Therefore, the toe of the moraine usually experiences the deposition of material eroded from the dam during the outburst (see the example of lake Jancarurish in Fig. 1). The exception with clear erosion below the elevation of the point where the stream leaves the dam is the South Lhonak lake outburst. The dam breach was followed by channel incision directly downstream the dam (Sattar et al., 2025). This could be explained by the direction of the outflow channel towards topographically rather narrow side of the valley (so the energy of the flow is not dissipated) with the presence of erodible colluvial material.

4.4 Concluding remarks

We analyzed the slope of the breach channels of world's largest outbursts from moraine-dammed lakes (outburst volume reportedly exceeding 10^6 m^3 in each case). Our analysis suggests that regardless the total flood volume (differing in order of two magnitudes in the dataset; from 10^6 to 10^8 m^3) and peak discharges exceeding 10^4 m^3/s, the incision of the outflow channel stops when it is flattened to a certain slope steepness (minimum observed steepness is 2.3°, median is 5.0°). This observation has two important implications for developing PFV scenarios:

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(i) Using this parameter threshold represents a simple way of estimating the worst-case scenario breach depths and potential flood volumes for moraine dam failure-induced lake outbursts (with both known or unknown bathymetries);

(ii) This threshold also suggests that outflow channels with the mean steepness < 3° are unlikely to be breached, especially in case of a wide moraine dam with several hundred meters long outflow channel.

We employed our new method to recalculated previously estimated worst-case scenario potential flood volumes, revealing that it tends to provide modest results. This fine-tuning of GLOF scenarios have clear implications for predictive modelling and so definition of GLOF exposed areas and hazard zones.

Code and data availability. The data analysed in this study (remote sensing data, climate reanalysis data) are freely available (see details in the main text). Any additional information will be provided by the corresponding author upon request.

Supplement. This submission includes supplementary materials:

Author contributions. AE developed research idea and analysed remote sensing data, AS and JH contributed to the discussion of research design and text production. In particular, AS elaborated parts related to GLOF modelling and JH elaborated parts dealing with physical controls of breach development.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Acknowledgement.

Financial support. The authors acknowledge financial support (APC coverage) by the University of Graz.

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