https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions
Open Access

A conceptual model for glacial lake bathymetric distribution

Taigang Zhang[1,2,3], Weicai Wang[2], Baosheng An[2,4]

[1]College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China

[2]State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[3]Center for the Pan-Third Pole Environment, Lanzhou University, Lanzhou 730000, China

[4]School of Science, Tibet University, Lhasa 850011, China

Correspondence: Taigang Zhang (zhangtg16@lzu.edu.cn) and Weicai Wang (weicaiwang@itpcas.ac.cn)

Abstract. The formation and expansion of glacial lakes worldwide due to global warming and glacier retreat have been well documented in the past few decades. Thousands of glacial lake outburst floods (GLOFs) originating from moraine-dammed and ice-dammed lakes were reported, causing devastating impacts on downstream lives and properties. Detailed glacial lake bathymetry surveys are essential for accurate GLOF simulation and risk assessment. However, these bathymetry surveys are still scarce as glacial lakes located in remote and high-altitude environments hamper a comprehensive investigation. We developed a conceptual model for glacial lake bathymetric distribution using a semi-automatic simulation procedure. The basic idea is that the statistical glacial lake volume-area curves conform to a power-law relationship indicating that the idealized geometric shape of the glacial lake basin should be hemispheres or cones. First, by reviewing the evolution of various types of glacial lakes, we identified 10 standard conceptual models to describe the shape of

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

lake basins. Second, we defined a general conceptual model to depict the continuum transitions between different standard conceptual models for those specific glacial lakes that lie between two standard conceptual models. Third, we nested the conceptual model into the actual glacial lake basin to construct the water depth contours and interpolate the glacial lake bathymetric distribution. We applied the conceptual model to simulate three typical glacial lakes in the Tibetan Plateau with in-situ bathymetric surveys to verify the algorithm's applicability. The results show a high consistency in the point-to-point comparisons of the measured and simulated water depths with a total volume difference of approximately ±10%. The conceptual model has significant implications for understanding glacial lake evolution and modeling GLOFs in the future.

1 Introduction

Globally, glacial recession and thinning have been well-documented over the last decades via field observations and remote sensing techniques (Yao et al., 2012; Zemp et al., 2019; Hugonnet et al., 2021). Such evolution of glaciers due to climate warming and anthropogenic factors could induce related effects (Yao et al., 2019), among which is the expansion and formation of glacial lakes (Zhang et al., 2015; Emmer et al., 2016; Wang et al., 2020; Ma et al., 2021). Glacial lakes are water bodies developed within depressions of glacier moraine or mainly fed by contemporary glacier meltwater (Yao et al., 2018). Due to glacier retreats, they are generally impounded by glacier terminal or lateral moraine. Since the 1990s, the glacial lakes worldwide have increased by around 50% in total number, area, and volume (Shugar et al., 2020), manifesting an ongoing climate change. These changes have also been accompanied by glacial lake outburst flood (GLOF) risks.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

As a glacier–related hazard, GLOF has been a frequent incidence in various glacierized areas, causing considerable socioeconomic losses (Anacona et al., 2015a; Nie et al., 2018). According to a compilation by Carrivick and Tweed (2016), approximately 1000 GLOFs from moraine- and ice-dammed lakes are recorded worldwide and claim more than 10000 deaths. Under the triggering factors such as ice avalanches, landslides, and heavy precipitation, glacial lakes are extremely unstable and subsequently cause a sudden release of water with peak discharge higher than a dozen times that of monsoon rainfall floods (Richardson and Reynolds, 2000; Westoby et al., 2014; Kougkoulos et al., 2018). However, due to the relatively small volume of the glacial lake, the flooding process generally proceeds rapidly within a few hours. Knowledge of glacial lake volume is critical, as it influences the released water volume and GLOFs magnitude (Fujita et al., 2013). Therefore, lake volume is often employed as an essential criterion in numerous cases of GLOF susceptibility and risk assessment (Bolch et al., 2011; Aggarwal et al., 2017; Drenkhan et al., 2019; Falatkova et al., 2019).

Currently, only sporadic bathymetric surveys on glacial lakes have been conducted worldwide. In Cordillera Blanca, Peru, facing continuous threats by GLOFs (Lliboutry et al., 1977), more than 100 detailed bathymetric surveys of glacial lakes have been carried out to understand better the regional GLOF risks (Muñoz et al., 2020). Government agencies and research institutions have promoted these surveys. In the Tibetan Plateau and its surroundings, the bathymetric surveys are focused on the glacial lakes in the Himalayas (Sharma et al., 2018; Watson et al., 2018), where approximately 60 bathymetric surveys of glacial lakes, such as the Cirenmaco, Jialongco, and Longbasaba Lake, were conducted (Yao et al., 2012; Wang et al., 2018; Li et al., 2021). They measure the water depth with ultrasonic devices onboard automatic uncrewed boats or manual

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

hovercrafts.

Performing a universal investigation campaign of lake bathymetry is impractical for thousands of glacial lakes in remote areas and high elevations. Instead, scholars typically utilize single total lake volume data rather than bathymetric distribution in GLOF modeling (Anacona et al., 2015b; Zhang et al., 2021). The lake volume is typically estimated by empirical equation, e.g., direct volume–area equation (O'Connor et al., 2001; Huggel et al., 2002; Loriaux and Casassa, 2013), or indirect area–mean depth/maximum depth/width equation (Wang et al., 2012), which have considerable uncertainty. There is no doubt that the measured and/or interpolated glacial lake bathymetric distribution have great merit that can precisely determine the maximum potential outburst volume of the glacial lake, serving to further simulate the GLOF propagation and evaluate downstream exposures (Frey et al., 2018; Sattar et al., 2021). Moreover, a bathymetry survey is also pivotal to understanding the interactions between the glaciers and their terminating lakes, as several studies have revealed that the proglacial lake bathymetric state can dominate the glacier terminal melting and calving regimes (Sugiyama et al., 2021).

Can we obtain glacial lake bathymetric distributions through modeling rather than in situ investigations? Previous studies have provided insights. Cook and Quincey (2015) preliminarily proposed that the same type of glacial lakes may have their idealized geometric shapes, which depict the evolution of glacial lakes' volume–area (V–A) relationship over time. For instance, the triangular cone is suitable to represent the idealized geometric shape of ice-dammed lakes dammed by glaciers and formed in the narrow valley. The idealized conceptual models of glacial lakes can be combined with the actual situations to project the glacial lake bathymetric distribution.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions
Open Access
EGU

An idealized lake basin is also helpful in constructing numerical or physical models. In the study of Veh et al. (2020), the conceptual model of glacial lakes was constructed as a semi-ellipsoid with a circular surface to calculate the released volume after the lake drainage. The surface area and height of the semi-ellipsoid refer to the glacier lake area and maximum water depth, respectively. Based on these instructive designs, we attempted to develop a procedure and algorithm for modeling glacial lake bathymetric distribution in this study. We first (i) retrieved as many as possible conceptual models for various types of glacial lakes by reviewing the evolutions of glacial lakes and analyzing the relationships between lake volumes and areas; (ii) explored the procedure and algorithm to estimate bathymetric distribution in conjunction with actual lake surface and basin shapes; and then (iii) discussed their implications and potential applications.

2 Data and methods

2.1 Compilation of glacial lake bathymetry

Analyzing the existing glacial lake bathymetries can help us reveal glacial lake water depth characteristics. To our knowledge, more than 60 articles have mentioned surveyed bathymetry data from glacial lakes. We integrated the prior studies and established an inventory of global glacial lake bathymetry (Supplementary material 1). The attributes included the name, location, survey time, area, volume, and maximum water depth. A total of 231 bathymetric data from 220 glacial lakes globally were compiled in the inventory (Fig. 1a).

2.2 Classification and evolution of different glacial lake types

The maximum water depth (D) and total volume (V) are the fundamental parameters regarding the idealized geometric shape of glacial lakes. We used the compiled glacial lake bathymetry data to fit the curves of V–A (glacial lake area) and D–A to understand the evolution of glacial lakes and to develop a conceptual model suitable for describing the shape of an idealized lake basin. We assumed that different types of glacial lakes have different expansion mechanisms and, thus, different conceptual models. Based on the topological positions between the glacial lakes and their parent glaciers, we classified glacial lakes as supraglacial proglacial, periglacial, extraglacial, and ice-dammed types (Fig. 1b).

This classification system considers glaciers' critical role in the evolution of glacial lakes (Petrov et al., 2017). As for the supraglacial lakes, expansion proceeds in all directions, and the temperature difference at the ice-water interface continuously melts the glacier ice in both horizontal and vertical orientations. The proglacial lake's expansion mainly proceeds backward by glacial retreat. The periglacial lake and the extraglacial lake are not directly in contact with the glacier, and their expansion depends more on changes in precipitation and glacier meltwater. These various mechanisms in glacial lake expansions showed that the changes in the lake basin among the different glacial lake types are inconsistent, indicating that they may have different conceptual models.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions
Open Access
EGU

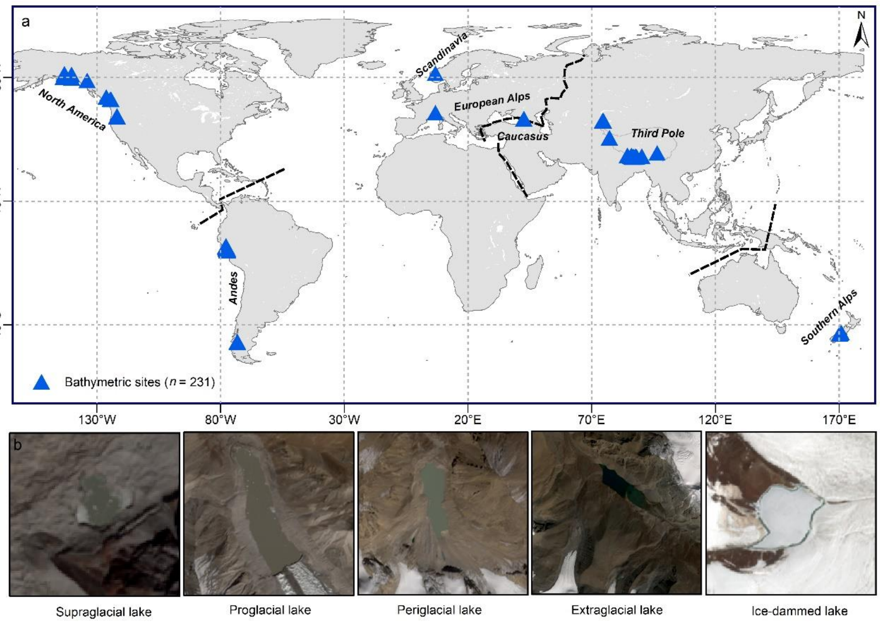

Figure 1. (a) Distribution of glacial lakes whose volume was surveyed in detail. (b) Glacial lakes were divided into five categories, namely proglacial (direct in contact with glacier terminus), periglacial (separated from the glacier and dammed by historical moraine), extraglacial (far from the glacier and generally dammed by landslides), supraglacial (positioned on the glacier surface), and ice-dammed lake.

2.3 Standard conceptual model

The basic procedure of constructing glacial lake bathymetric distribution is to (i) identify the most appropriate conceptual model that can describe the idealized lake basin, (ii) calculate the theoretical formulation equations of this conceptual model, (iii) nest this conceptual model into the actual glacial lake basin to construct the water depth contours, and (iv) interpolate and calculate the glacial lake bathymetric distribution. The conceptual model was constructed as the scheme presented by Veh et al. (2020). Glacial lakes were assumed to have hemispherical or similar three-

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

dimensional lake basin shapes. The standard surface of the glacial lake was assumed to be an ellipse.

The general formula between the volume and area of glacial lakes fits a power-law relationship (Table 1). It could be expressed as Eq. (1). The best-fit curve for the relationship between maximum water depth and area of glacial lakes also follows the power-law relationship (Eq. 2) (Fig. 2).

$$V = \alpha A^{\beta} \qquad (1)$$

$$D = \gamma A^{\varepsilon} \qquad (2)$$

A is the area of the glacial lake; α, γ, β, and ε are the coefficients. The value of β is greater than 1, and ε is less than 1.

The three-dimensional bodies representing the standard shape of a lake basin were required to have a general formula as defined by Eq. (3):

$$V = \delta AD \qquad (3)$$

Here, δ is the coefficient, A is the elliptical surface area, and D corresponds to the maximum water depth of the glacial lake. We identified four hemispheres or cones whose volumes can be expressed by Eq. (3): the hemisphere structured by the elliptical side ($V = 2/3AD$); the hemisphere structured by the upward-opening parabolic side ($V = 1/2AD$); the cone structured by the straight side ($V = 1/3AD$); and the cone structured by the rightward-opening parabolic side ($V = 1/5AD$). These bodies are defined as the standard conceptual model (SCM), and their curves in the X-O-Z quadrant are called the standard curves (Fig. 3a). These four standard curves are progressively concave inward in the quadrant, from the elliptical curve to the rightward-opening parabolic curve.

The SCMs for the supraglacial, periglacial, and extraglacial lake types are compatible with the

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

expansion mechanisms partly because their growth direction is comprehensive at the horizontal level. However, proglacial lakes are different. Their expansions are focused toward the glacier's direction, and the maximum water depths are situated near the intersection with the glacier. Under these circumstances, we considered the SCMs of proglacial lakes to be half of the preceding four SCMs, such as the semi–cone structured by the straight side. We also took into account the way in which the SCMs of the ice-dammed lake formed. We ultimately designed two SCMs: the semi–cone structured by the straight side and the triangular cone ($V = 1/3A \cdot D$). Most of the actual volume points lie between the volume curves of these SCMs (Fig. 4), and there are one or two closer SCM volume curves for each type of glacial lake's fitted A–V curve.

Table 1. Empirical equations of volume and area of glacial lakes in previous studies. The applicable region, lake type, and sample size for each empirical equation were indicated during fitting. The unit volume is 10^6 m^3, and the area unit is km^2.

ID	Empirical formulas	Region	Lake types	Samples	Reference
1	$V = 35A^{1.5}$	British Columbia, Canada	Ice-dammed lake	not mentioned	Evans, 1986
2	$V = 168.5A^2 + 3.11A$	Northwestern America	Moraine-dammed lake	7	O'Connor et al., 2001
3	$V = 34.44A^{1.42}$	Worldwide	Moraine- and ice-dammed lake	13	Huggel et al., 2002
4	$V = 43.24A^{1.53}$	Himalayas	Moraine-dammed lake	17	Sakai, 2012
5	$V = 6.07A^{1.37}$	Himalayas	Moraine-dammed lake	20	Wang et al., 2012
6	$V = 55A^{1.25}$	Himalayas	Moraine-dammed lake	20	Fujita et al., 2013
7	$V = 33.58A^{1.39}$	Worldwide	Moraine- and ice-dammed lake	31	Loriaux and Casassa, 2013

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

8	$V = 42.93A^{1.48}$	Peruvian Andes	Moraine- and bedrock-dammed lake	35	Emmer and Vilímek, 2014
9	$V = 34.07A^{1.37}$	Worldwide	Various types	69	Cook and Quincey, 2015
10	$V = 11.49A^{1.26}$	Worldwide	Supraglacial lake	9	Cook and Quincey, 2015
11	$V = 60A – 6.28$	Worldwide	Moraine-dammed lake	42	Cook and Quincey, 2015
12	$V = 2.63e^{A}$	Worldwide	Ice-dammed lake	9	Cook and Quincey, 2015
13	$V = 37.3A^{1.47}$	Himalayas	Moraine-dammed lake	33	Khanal et al., 2015
14	$V = 52.2A^{1.18}$	Himalayas	Proglacial lake	6	Sharma et al., 2018
15	$V = 40A^{2} + 5.06A$	Himalayas	Moraine-dammed lake	17	Patel et al., 2017
16	$V = 35.36A^{1.47}$	Central Asia	Moraine-dammed lake	32	Kapitsa et al., 2017
17	$V = 32.13A^{1.49}$	Himalayas	Ice-dammed lake, supraglacial lake	not mentioned	Miles et al., 2018
18	$V = 28.95A^{1.33}$	Worldwide	Moraine-dammed lake	93	Watson et al., 2018
19	$V = 35.46A^{1.4016}$	Himalayas	Supraglacial lake	24	Watson et al., 2018
19	$V = 41WA + 2A$	Cordillera Blanca, Peru	Moraine-dammed lake	120	Muñoz et al., 2020
20	$V = 37.36A^{1.41}$	Peruvian Andes	Various types	170	Wood et al., 2021
21	$V = 38.04A^{1.36}$	Peruvian Andes	Moraine-dammed lake	not mentioned	Wood et al., 2021
22	$V = 43.27A^{1.64}$	Peruvian Andes	Unclassified	not mentioned	Wood et al., 2021

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere
Discussions
Open Access

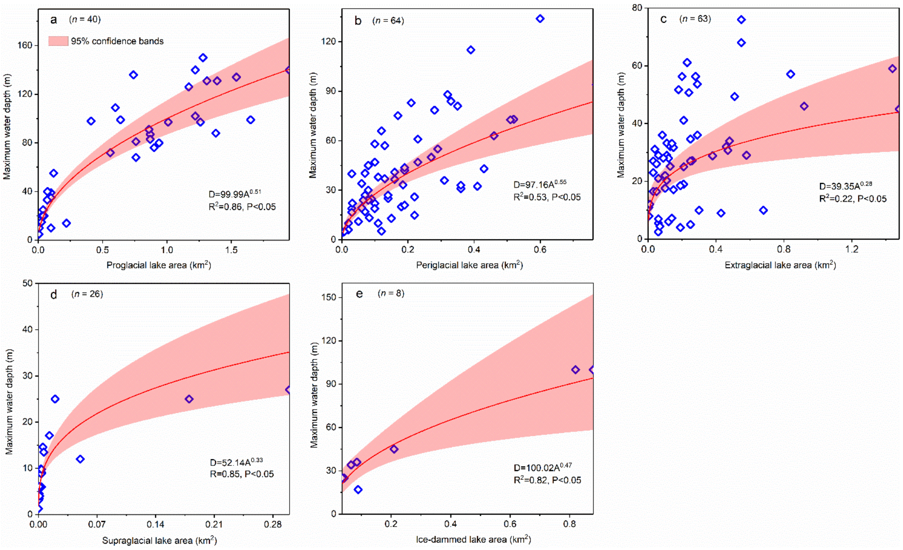

Figure 2. Relationships between maximum water depth and the area of glacial lakes were compiled in the present study for the following lake types: (a) proglacial lake, (b) periglacial lake, (c) extraglacial lake, (d) supraglacial lake, and (c) ice-dammed lake.

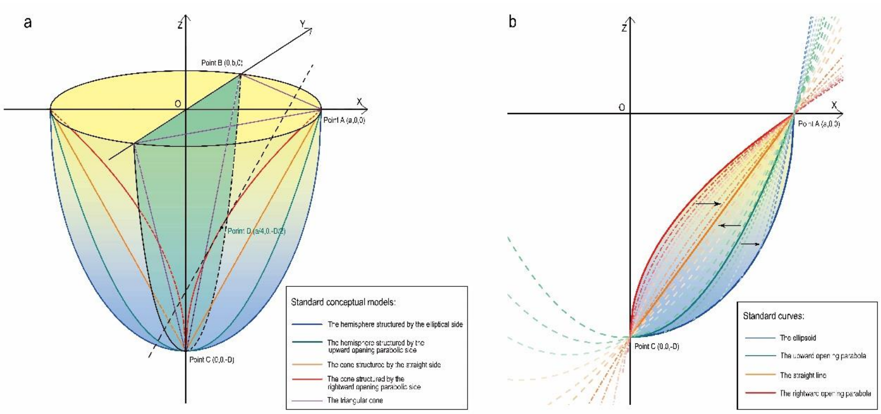

Figure 3. (a) Schematic diagram illustrates the shapes of the SCMs, namely the hemisphere structured by the elliptical side/upward-opening parabolic side, the cone structured by the straight side/rightward-opening parabolic side, the triangular cone, as well as their shapes when symmetrically divided matching the SCMs of the proglacial

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

lake. Here, A is the semi-long axis, B is the elliptical surface's semi-short axis, and D is the maximum water depth.

(b) Convergences of the general curves towards the standard curves in the X–O–Z quadrant in different orientations.

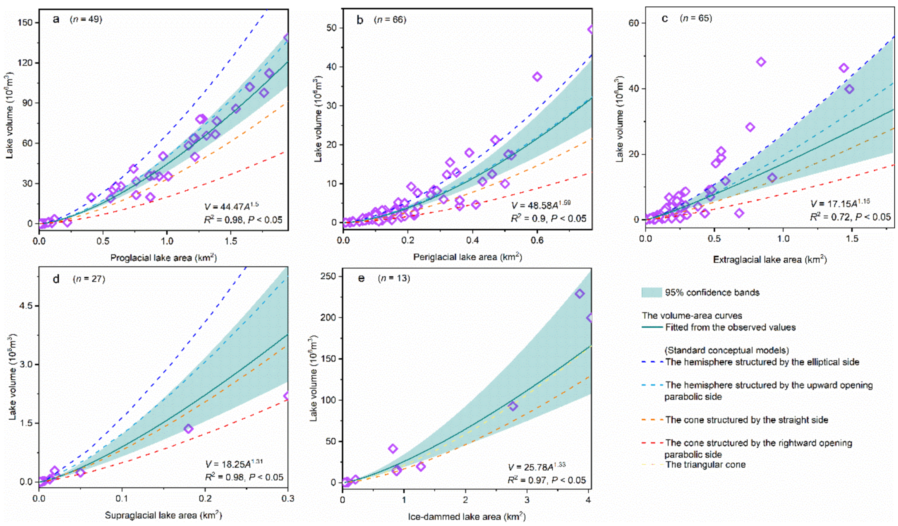

Figure 4. Relationships between the volume (V) and area (A) of glacial lakes were compiled in the present study for the following lake types: (a) proglacial lake, (b) periglacial lake, (c) extraglacial lake, (d) supraglacial lake, and (c) ice-dammed lake. The dotted lines indicate the volume curves of different standard conceptual models, which were fitted by Eq. (3). The V–A curves of standard conceptual models of the proglacial lake type are half the normal condition.

2.4 General conceptual model

The closest SCM likely does not represent the most appropriate conceptual model if a specific glacial lake determines its parameters such as surface size, type, and volume. The SCM volume curve is constant. However, the volume point of a specific glacial lake does not necessarily coincide with the SCM volume curve. Thus, using the SCM directly to nest and interpolate a realistic glacial lake bathymetric distribution would result in an initial over- or underestimation of the total lake

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions

volume.

The SCMs can only help us comprehend the various glacial lake morphologies; they cannot be applied to estimate the glacial lake bathymetric distribution. We may conceive the measured volume points between the SCM volume curves as a result of the transition from one SCM to another. For instance, from the upward-opening parabolic line to the straight line, it is the standard parabolic line continuously approximating the straight line on the X–O–Z quadrant by moving downward and left (Fig. 3b). During the movement process, the rotated–out hemisphere is moving toward the cone structured by the straight side. We can capture these general conceptual models (GCMs) in this transition stage and make their volume consistent with the measured or estimated lake volume. This means we find a GCM that is more effective than the SCM in estimating the lake depth distribution.

Python programming was used to drive the standard curves' transition and parameter calculations. The theoretical description for the GCMs is presented in supplementary material 2. By relocating the standard curve's vertices and altering the opening size, it is simple to compute the transition of a standard upward/rightward-opening parabola to a straight line. The resultant general curves must pass through points A and C. The convergence to the standard elliptic curve from the standard upward-opening parabola is relatively complicated. If we move the vertices of the standard parabola to the right and downward, the maximum height of the produced GCM changes. We used a compound style here. When the second intersection of the moved general parabolic curve and the standard elliptic curve occurs (from right to left), the side of GCM starts to take the elliptic curve change. Additionally, the marginal SCMs should be employed when the measured volume is larger (smaller) than the largest (smallest) SCM volume.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

2.5 Nesting the actual glacial lake shapes

Once a given glacial lake's GCM has been established, the lake's bathymetric contours may be predicted in relation to actual conditions and parameters. Since the actual shape of the glacial lake surface is irregular, rather than the normal elliptic surface we used in the models, it was crucial to how the depth contours move inward based on the actual shape.

We tested two hypotheses. First, utilizing the lakeshore line to continually create buffers inward might depict the depth contours because the depth contours near the lakeshore were the consequence of ongoing indentation of the actual glacial lake surface outline inward. Second, at the 1/4 semi-long axis of the standard elliptic surface, the depth contours would become progressively blurred as the inward indentation continues, thus subsequently using the standard elliptic surface to start the inward indentation (Fig. 5). Importantly, these assumptions were supported by observations of hundreds of glacial lake bathymetric distribution cases worldwide. Some similarities exist between the bathymetric contours and the lakeshore shape, suggesting that the area near the lakeshore is possibly impacted by the slopes around the lake and/or other material sources. There are two explanations for this phenomenon: either the glacial lakes were continuously filled with exogenous debris and rocks, or the initial lake water level had risen and flooded part of the original slopes.

The 1/4 semi–long axis is the ending position where the glacial lake is not impacted by exogenous materials, as determined by our understanding of those SCMs. Most of the glacial lake SCMs were located closer to the cone, structured by the straight side of the hemisphere and the upward-opening parabolic side. It is inferred that the initial deepening of the glacial lake is not particularly large from the outer line to the center (compared to the semi–ellipsoid), indicating that

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

exogenous materials are likely to have impacted it. This situation is better understood when the lake SCM is a cone structured by the rightward-opening parabolic side. Therefore, we hypothesized an extreme circumstance in which a glacial lake starts to be significantly influenced by the lake's surroundings' topography. In this case, the slope of the standard rightward-opening parabolic curve is smaller than the slope of the standard straight line and closer to the ideal deepening state of the lake basin when it is larger. This equal slope point is located at the 1/4 semi-long axis and represents half of the maximum water depth.

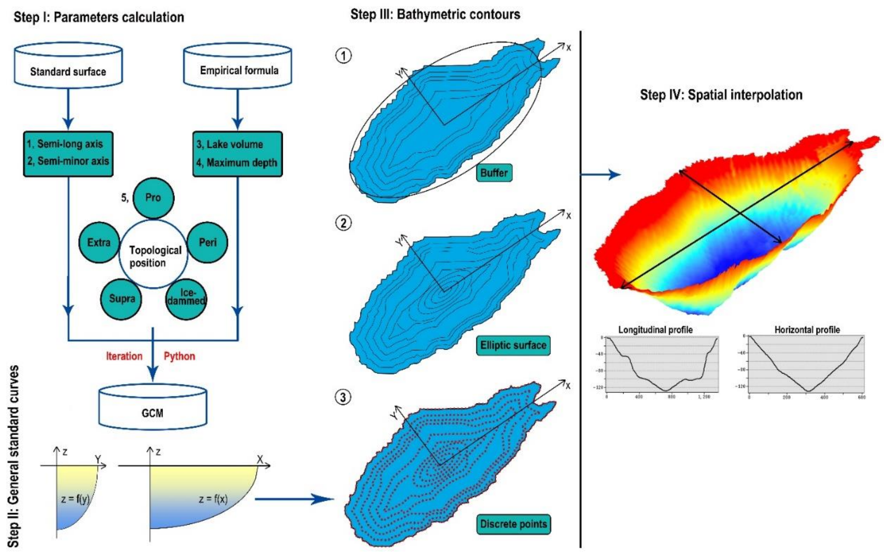

Figure 5. The procedure illustrates the parameter calculation of GCMs and processes of creating buffers inward. The water depths on the axes were calculated using the standard curves corresponding to the X and Y axes.

2.6 Sites for exhibiting and validating results

Three sets of bathymetry data were collected for the typical glacial lakes in the Himalayas, Tibetan Plateau (Fig. 6). Cirenmaco and Jialongco, periglacial lakes, are located in the Poiqu River basin (China-Nepal border). Both lakes experienced GLOFs in 1981 and 2002, causing severe

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions
Open Access
EGU

infrastructure losses and transboundary damages (Chen et al., 2013). The Longbasaba Lake at the China–India border is a benchmark proglacial lake that has been studied in detail for the glacial lake risks and dynamics of the lake-terminating glaciers (Yao et al., 2012; Wei et al., 2021). The topological position, total volume, maximum water depth, and semi-long/minor axis of the standard lake surface were crucial parameters in glacial lake bathymetric distribution modeling (Table 2). The three glacial lake bathymetric distributions were simulated according to the lake sizes in the survey year and eventually compared with the measured points of water depths to verify the feasibility and accuracy of our modeling method.

Table 2. The crucial modeling parameters of the three selected glacial lakes.

Name	Topological position	Survey year	Volume (10^6 m^3)	Maximum water depth (m)	Semi-long axis (m)	Semi-minor axis (m)
Jialongco	peri	2020	37.5	133	757	314
Cirenmaco	peri	2012	18.0	115	549	185
Longbasaba Lake	pro	2009	64.0	102	1949	319

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

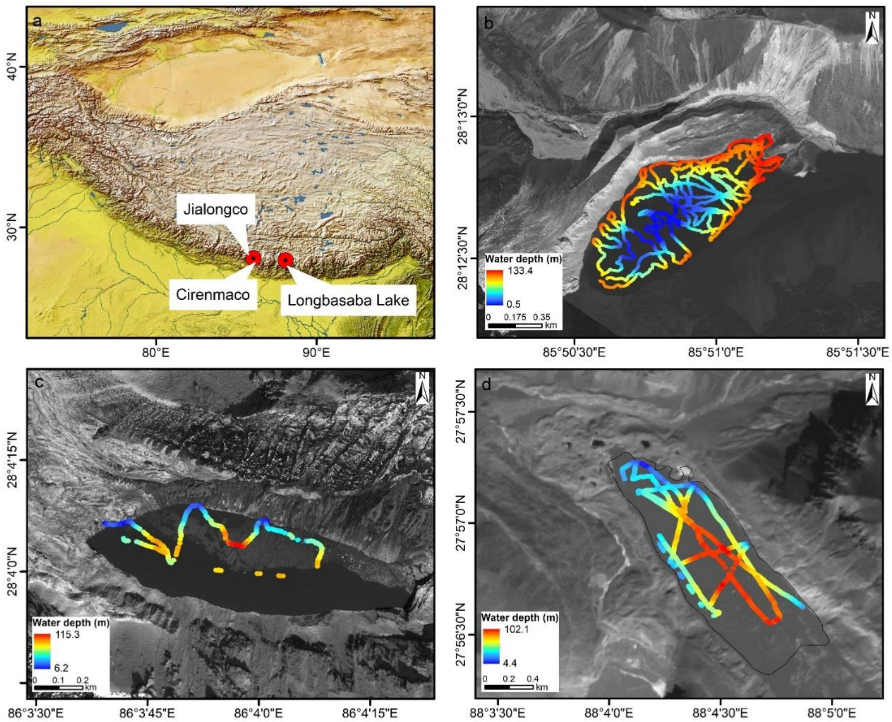

Figure 6. (a) Locations of Cirenmaco, Jialongco, and Longbasaba Lake, and (b, c, d) indications for their water depths along the bathymetric routes.

3 Results

We present the SCMs for each type of glacial lake and demonstrate a procedure to identify the most compatible GCM for a specific glacial lake by equalizing the volume of both. This is the only (or first) model to simulate the bathymetric distribution of glacier lakes at present. The results indicate that the proglacial and periglacial lakes are relatively deep because their SCMs are closer to the hemisphere structured by the upward-opening parabolic side. The SCMs of the extraglacial and supraglacial lakes are closer to the cone structured by the straight side. As the ice-dammed lake,

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

their V–A fitting curve is more similar to the V–A curve of the triangular cone (Fig. 3). Hence, we recommend that the bathymetric distribution modeling for ice-dammed lakes proceeds directly using the standard triangular cone and is not further explored in this study.

We determined the optimal GCMs for the three exhibited glacial lakes. Following bathymetric distribution modeling results, the total volume of Jialongco was calculated to be 33.1×10^6 m^3 (−11.7%) with a mean water depth of 54.6 m (−8.1%). Its GCM was closer to the cone structured by the straight side (Fig. 7a). The computed Cirenmaco total volume and mean depth of Cirenmaco were 17.2×10^6 m^3 (−4.4%) and 51.7 m (−6.9%), respectively. The Cirenmaco GCM had similarities with the hemisphere structured by the upward-opening parabolic side (Fig. 7b), meaning a more significant inward deepening rate than Jialongco. The proglacial lake, Longbasaba, was estimated to have a total volume of 71.4×10^6 m^3 (11.5%) and a mean depth of 61.1 m (22.2%). Its GCM was more resemblant to the semi-ellipsoid (Fig. 7c). Approximately ±10% volume loss or increase was estimated in the process of nesting the general conceptual models to the actual glacial lake shapes.

The disparity between the area of the assumed standard ellipse surface and the actual lake surface likely caused the majority of the inaccuracy. The initial settings of glacial lake conceptual models and the algorithm's applicability were confirmed by comparison with the measured and estimated individual water depths. Between the estimated and measured water depths along the bathymetric routes, the average deviation, mean absolute deviation, and mean root square error for the three glacial lakes all described good consistency. Neither near the lakeshore nor the lake center do the estimates show intolerable dispersions.

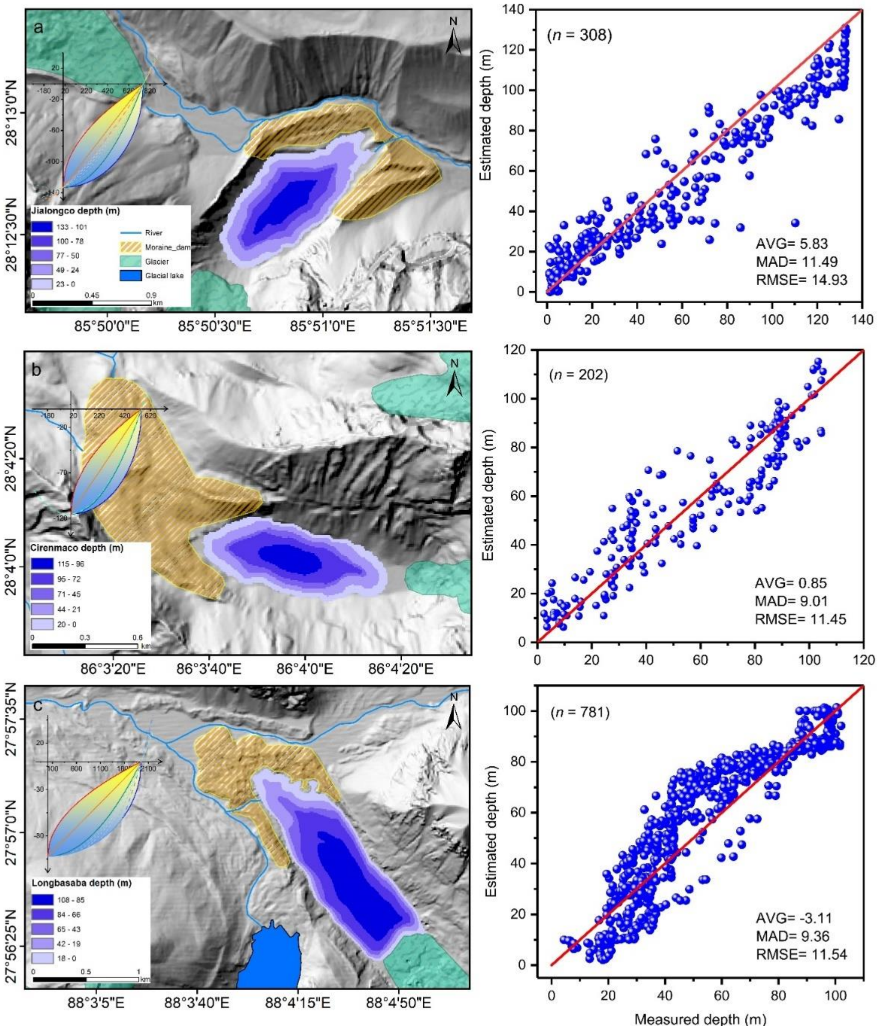

Figure 7. Modeled glacial lake bathymetric distributions of the three selected glacial lakes. (a) Jialongco, (b) Cirenmaco, and (c) Longbasaba Lake. The average deviation (AVG), mean absolute deviation (MAD), and root mean square error (EMSE) were selected to depict the consistency between the simulated and measured individual water depths along the boat routes. The movements of the general curves from one standard curve to another are also indicated.

4 Discussion

4.1 Glacial lake basin evolution

Understanding the glacial lake evolution can help comprehend these idealized geometric shapes in theory. Most moraine- or bedrock-dammed lakes develop in depressions exposed by diminishing glaciers. The supraglacial lakes exist at the glacier snout, eventually facilitating the formation of proglacial and periglacial lakes (Carrivick and Tweed, 2013). As the three glacial lakes illustrated, our hypotheses explained the different rates of inward deepening with exogenous materials and boundary conditions impacting the glacial lakes. The glacier bedrock has been eroded and nudged during historical ice flowing, posing the excavation and growth of glacial lake basins.

Contemporary glaciers often have a certain thickness of debris at the snout. For example, approximately 1 m of debris was observed at the snout of the Urumqi Glacier No. 1, China (Echelmeyer et al., 1987) as the result of glacial erosion. The specific sites of continual eroding and nudging spawn overdeepenings and are considered potential glacial lakes (Linsbauer et al., 2016). Since the glacier velocity in the middle part is often larger than that of both sides, the erosion is stronger in the central line of the initial overdeepening. As glacier flowing continues, the shape of the overdeepening finally reaches equilibrium and is similar to a hemisphere, which is the SCM of the lake basin we assumed. After the overdeepenings are exposed, they can be filled by meltwater to form glacial lakes while also receiving material deposition, resulting in a gradual transition of the idealized geometric basin from a hemisphere to a cone. This conjecture can be inferred from the studies of overdeepenings on glacial beds, whereby the volume and surface area of these potential glacial lakes are also in accordance with the power-law relationship (Zhang et al., 2022).

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions
Open Access
EGU

4.2 Applicability of the conceptual model

Our modeling theory is based on the observation of glacial lake bathymetric distribution characteristics. The fitted curves of glacial lake volume-area/maximum water depth were derived from the compiled inventory of 231 bathymetric data globally, and thus this modeling approach is applicable to most glacial lakes in mountain glaciers. The designed conceptual model is more suitable for those glacial lakes with typically lengthy shapes. They may be less applicable for very irregularly shaped glacial lakes, such as the ice-marginal lakes in the Greenland and Alaska region. Similarly, we had not collected any glacial lake bathymetry data in polar regions which causes non-applicability on supraglacial lakes over the Greenland/Antarctic Ice sheets. Although the simulated results were only validated in the Himalayan region due to the limitations of observation data, the comparison results of the measured and modeled depth values at different locations of the three glacial lakes reflect the rationality and reliability of our conceptual model. To our knowledge, roughly 80% of glacial lakes in the Tibetan Plateau and its surroundings can be modeled using this method.

In addition to the subjective and objective errors made during the modeling phase, there are several systematic defects in the algorithm itself. First, the total volume and maximum water depth are calculated using empirical equations, which may lead to significant deviations when modeling the bathymetric distribution of an arbitrarily selected glacial lake. In particular, the curves of D–A are not robust, with many discrete points appearing. This affects the modeling results. Therefore, rather than employing the curves based on global bathymetry statistics, fitting and using more accurate regionally empirical formulae to reveal local glacial lake features is encouraged.

Second, the estimated depth contours converge inward using the lake shoreline buffers first, followed by the elliptical surfaces. This process may effectively simulate the connections between a bathymetric distribution and glacial lake morphology. However, it is not essential. If the elliptical indentations are always inward relative to the elliptical surface, the modeling accuracy is also not affected significantly in theory.

Third, the deepest sites of supraglacial, periglacial, and extraglacial lakes have been considered to be in the lake center and near the glacier-lake interface for proglacial lakes and ice-dammed lakes. The developing proglacial lakes, however, are complex. Their deepest sites are constantly located near the glacier terminus before the deepest site of overdeepening is exposed, which is in accordance with our hypothesis. With the deepest sites developing more fully, they gradually shift toward the lake center. Our algorithm has not addressed these changes. In the future, the conceptual model requires optimization by learning with a number of measured bathymetry data. Furthermore, the present version of our algorithm relies on simple programming and semi-automated geospatial analysis tools processing. We will further develop this conceptual model to create an interface that can automatically process and lessen subjective errors.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

The Cryosphere Discussions
Open Access
EGU

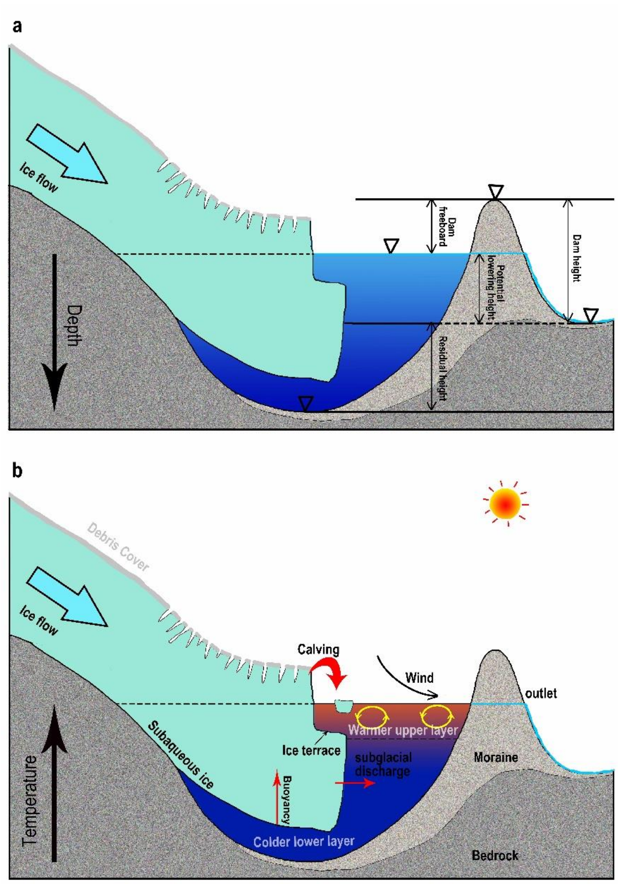

Figure 8. The schematic diagrams illustrate (a) the potential maximum lowering height of the glacial lake water level after drainage and (b) the interactions between the parent glacier and its terminating lake.

4.3 Applications in GLOF modeling

The applicability of a glacial lake bathymetric distribution has been addressed in this study; one such application is in GLOF modeling. The results make two significant contributions to future GLOF modeling: (i) accurately estimate the maximum potential outburst water volume of a glacial lake by combining lake surface elevation, dam bottom elevation, and the optimal GCM; (ii) facilitate coupling between the various GLOF processes in modeling (trigger—displacement wave—dam

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

breach—flood propagation). Many recent studies have documented reconstructing the historical GLOFs and simulating the future GLOFs from high outburst potential glacial lakes (Allen et al., 2015; Anacona et al., 2015b; Erokhin et al., 2017; Kougkoulos et al., 2018). The modeling precision is expected to improve significantly.

On the one hand, most prior studies replaced the potential maximum outburst volume with the total water volume because of the limitations of glacial lake bathymetric investigations (Zhang et al., 2021). Although this could present a maximized risk assessment, an inflated downstream exposure might raise excessive concerns among the authorities and the public regarding inadequate prevention and mitigation measures. As long as the dam's lowest elevation exceeds that of the glacial lake (potential lowering height is less than the maximum water depth), it could result in incomplete drainage (Fig. 8a).

On the other hand, due to the complicated phase transition in the chain process of GLOFs, a segmented simulation has been generally conducted. For instance, Rapid Mass Movement Simulation (RAMMS) can be used to simulate the impact of ice avalanches or landslides on glacial lakes (Frey et al. 2018; Sattar et al. 2021), and hydrological algorithms are used to calculate the displacement wave (Heller et al. 2009; Evers et al. 2019). Modeling software like IBER, HEC-RAS, or FLO-2D are employed to simulate downstream flood propagation (Alho and Aaltonen, 2008; Osti and Egashira, 2009; Schneider et al., 2014; Somos-Valenzuela et al., 2015; Maurer et al., 2020; Nie et al. 2020).

In contrast to a holistic simulation, such a segmented simulation approach undoubtedly causes poor articulation and increased uncertainty in different processes. With the recent scientific

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

developments, a newly developed three-phase flow model, r.avaflow (Mergili et al., 2017), started to be used to simulate GLOF propagations (Mergili et al., 2018, 2020) and can realize the whole hazard cascade modeling with a high performance (Zheng et al., 2021). Our study can provide much-needed glacial lake bathymetry data for such modeling to calculate the displacement wave in the lake surface and the water release process during dam erosion.

4.4 Potential developments of numerical or physical models

The standardized glacial lake basin can facilitate other future model development related to glacial lakes and improve knowledge of how the proglacial lakes and lake-terminating glaciers interact. Carrivick et al. (2020) discussed six major challenges in constructing a numerical model of interactions between proglacial lakes and glaciers, which include the imperative for glacial lake bathymetry. The standardized shape implicates the design of the model's basic architecture.

Compared with the somewhat realistic glacier bed topography within the overdeepenings revealed by Ice Thickness Models, a standardized lake basin provides an alternative scheme. For a specific proglacial lake, its water level, water temperature, in/outflow, internal circulation, and interface with the glacier vary with glacier-lake dynamics and time, which are very complex processes (Sugiyama et al., 2016; Sutherland et al., 2020). Deep and large proglacial lakes are prone to water stratification due to warmer upper layers and colder lower layers of water because these freshwater terminating lakes currently have no evidence of active internal circulation (Haresign and Warren, 2005; Boyce et al., 2007). This stratification induces the subaqueous ice differential melting and ice terrace formation (Fig. 8b), impacting the glacier terminal calving regimes (Sugiyama et al., 2019; Mallalieu et al., 2020).

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

On the other hand, the dynamic characteristics of glacier snout, such as bed friction, longitudinal stress, and ice flow velocity, vary distinctively due to the presence of terminating lakes (Sugiyama et al., 2011; Liu et al., 2020). The knowledge and understanding of glacial lakes formation and evolution changes continually. The ultimate goal is to present these processes via computer numerical simulations. Yet, the idealized lake basin can facilitate calculating the mass and energy transport at the interface.

5 Conclusion

This study was conducted in response to a circumstance that field investigation was the only approach to obtain glacial lake bathymetry. The relationships of volume–area and maximum water depth–area of glacial lakes were reanalyzed via an inventory of the global glacial lake bathymetry data we compiled. The obtained curves were matched with a power-law relationship. Thus, the types of hemispheres or cones were determined as the conceptual models (idealized geometric shapes) of glacial lakes. The standard lake surface was assumed to be an ellipse.

Ten standard conceptual models were identified. The SCMs for the supraglacial, periglacial, and extraglacial lakes are the hemisphere structured by the elliptical side; the hemisphere structured by the upward-opening parabolic side; the cone structured by the straight side; and the cone structured by the rightward-opening parabolic side. The SCMs for the proglacial lakes were determined to be half of the aforementioned four SCMs. Two SCMs were considered for the ice-dammed lakes: the semi–cone structured by the straight side and the triangular cone. To depict the volume between the two SCMs, a general conceptual model was defined that represents the

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

transition from one SCM to another.

Several hypotheses are important in our algorithm to nest the actual glacial lake shapes from idealized conceptual models and interpolate glacial lake bathymetric distribution. First, the supraglacial, periglacial, and extraglacial lakes' deepest sites were assumed to be in the lake center, whereas the proglacial lakes and ice-dammed lakes' deepest sites were near the glacier-lake interface. Second, the effects of exogenous materials and boundary conditions were used to explain the different rates of inward deepening of glacial lakes. Three glacial lakes with measured bathymetry data were selected in the Himalaya region for comparison with the simulated bathymetric distributions. The results demonstrated good accuracy and applicability of our conceptual models in estimating lake bathymetry. Relatively high consistency was shown in the point-to-point comparisons of the measured and simulated water depths.

This study constructed the glacial lake bathymetric distribution model in first which is very rewarding for comprehending the evolution of glacial lakes. Moreover, the quality of GLOF modeling and risk assessment is also enhanced by our outlined general conceptual model. These standardized lake basins implicate the design of the model's basic architecture, which can potentially promote the development of future numerical or physical models of glacial lakes.

Code availability. The codes for calculating the functional equations of a general conceptual model in the coordinate axes are available on request.

Data availability. The observed bathymetric data of Jialongco and Longbasaba Lake were provided by Dr. Xiaojun Yao and Shangguan Donghui, respectively.

Supplement. The supplement related to this article is available online at:

Author contributions. TZ designed the study, compiled the data and drafted the manuscript. WW and BA revised and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Financial support. This study was supported by the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program (2019QZKK0208); the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20100300); and the International Partnership Program of Chinese Academy of Sciences (131C11KYSB20200029).

References

Aggarwal, S., Rai, S. C., Thakur, P. K., and Emmer, A.: Inventory and recently increasing GLOF susceptibility of glacial lakes in Sikkim, Eastern Himalaya, Geomorphology, 295, 39–54, http://dx.doi.org/10.1016/j.geomorph.2017.06.014, 2017.

Alho, P., and Aaltonen, J.: Comparing a 1D hydraulic model with a 2D hydraulic model for the simulation of extreme glacial outburst floods, Hydrol. Process, 22, 1537–1547. http://dx.doi.org/10.1002/hyp.6692, 2018.

Allen, S. K., Rastner, P., Arora, M., Huggel, C., and Stoffel, M. (2016). Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition, Landslides, 13, 1479–1491, http://dx.doi.org/10.1007/s10346-015-0584-3, 2015.

Anacona, P. I., Mackintosh, A., Norton, K. P.: Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes, Earth Surf. Process Landf., 40, 2–21, http://dx.doi.org/10.1002/esp.3524, 2015a.

Anacona, P. I., Mackintosh, A., Norton, K.: Reconstruction of a glacial lake outburst flood (GLOF) in the Engano Valley, Chilean Patagonia: Lessons for GLOF risk management, Sci. Total Environ., 527–528, 1–11, http://dx.doi.org/10.1016/j.scitotenv.2015.04.096, 2015b.

Bolch, T., Buchroithner, M. F., Peters, J., Pradhan, B., Buchroithner, M., and Blagoveshchensky, V.: Identification of glacier motion and potentially dangerous glacial lakes in the mt. Everest region/Nepal using spaceborne imagery, Nat. Hazard Earth Syst., 8, 1329–1340, http://dx.doi.org/10.1007/s11069-011-9860-2, 2011.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

Boyce, E. S., Motyka, R. J., and Truffer, M.: Flotation and retreat of a lake-calving terminus, Mendenhall Glacier, southeast Alaska, USA, J. of Glaciol., 53, 211–224, http://dx.doi.org/10.3189/172756507782202928, 2007.

Carrivick, J. L., and Tweed, F. S.: Proglacial lakes: character, behaviour and geological importance, Quat. Sci. Rev.,78, 34–52, http://dx.doi.org/10.1016/j.quascirev.2013.07.028, 2013.

Carrivick, J. L., and Tweed, F. S.: A global assessment of the societal impacts of glacier outburst floods, Glob. Planet. Change, 144, 1–16, http://dx.doi.org/10.1016/j.gloplacha.2016.07.001, 2016.

Carrivick, J. L., Tweed, F. S., Sutherland, J. L., and Mallalieu, J.: Toward numerical modeling of interactions between ice-marginal proglacial lakes and glaciers, Front. Earth Sci., 500, https://doi.org/10.3389/feart.2020.577068, 2020.

Chen, N. S., Hu, G. S., Deng, W., Khanal, N., Zhu, Y. H., and Han, D.: On the water hazards in the trans-boundary Kosi River basin, Nat. Hazard Earth Syst. Sci., 13, 795–808, http://dx.doi.org/10.1007/978-981-10-2890-8_17, 2013.

Cook, S. J., Quincey, D. J.: Estimating the volume of Alpine glacial lakes, Earth Surf.. Dyn, 3, 559–575, http://www.earth-surf-dynam.net/3/559/2015/doi:10.5194/esurf-3-559-2015, 2015.

Drenkhan, F., Huggel, C., Guardamino, L., and Haeberli, W.: Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin, Sci. Total Environ., 665, 465–483, https://doi.org/10.1016/j.scitotenv.2019.02.070, 2019.

Echelmeyer, K., Wang Z. X.: Direct observation of basal sliding and deformation of basal drift at sub-freezing temperatures, J. Glaciol., 33, 83–98. http://dx.doi.org/10.3189/s0022143000005396, 1987.

Emmer, A., and Vilímek, V.: New method for assessing the susceptibility of glacial lakes to outburst floods in the Cordillera Blanca, Peru, Hydrol. Earth Syst. Sci., 18, 3461–3479, http://www.hydrol-earth-syst-sci.net/18/3461/2014/doi:10.5194/hess-18-3461-2014, 2014.

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V. and Cochachin, A.: 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods, Catena, 147, 269–279, http://dx.doi.org/10.1016/j.catena.2016.07.032, 2016.

Erokhin, S. A., Zaginaev, V. V., Meleshko, A. A., Ruiz-Villanueva, V., Petrakov, D. A., Chernomorets, S. S., Viskhadzhieva, K. S., Tutubalina, O. V., and Stoffel, M.: Debris flows triggered from non-stationary glacier lake outbursts: the case of the Teztor Lake complex (Northern Tian Shan, Kyrgyzstan), Landslides, 15, 83–98, http://dx.doi.org/10.1007/s10346-017-0862-3, 2018.

Evans, S. G.: The maximum discharge of outburst floods caused by the breaching of man-made and natural dams, Can. Geotech. J., 23(3), 385–387, http://dx.doi.org/10.1139/t87-062, 1986.

Evers F. M., Heller, V., Fuchs, H., Hager, W. H., and Boes, R. M.: Landslide-generated Impulse Waves in Reservoirs:

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

Basics and Computation, VAW-Mitteilungen, 254, 2019.

Falatkova, K., Šobr, M., Neureiter, A., Schöner, W., Janský, B., Häusler, H., Engel, Z., and Beneš, V.: Development of proglacial lakes and evaluation of related outburst susceptibility at the Adygine ice-debris complex, northern Tien Shan, Earth Surf. Dyn., 7, 301–320, https://doi.org/10.5194/esurf-7-301-2019, 2019.

Frey, H., Huggel, C., Chisolm, R. E., Baer, P., McArdell, B., Cochachin, A., and Portocarrero, C.: Multi-source glacial lake outburst flood hazard assessment and mapping for Huaraz, Cordillera Blanca, Peru, Front. Earth Sci., 6, 210. https://doi.org/10.3389/feart.2018.00210, 2018.

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A. B., Sawagaki, T., and Yamanokuchi, T.: Potential flood volume of Himalayan glacial lakes, Nat. Hazard Earth Syst. Sci., 13, 1827–1839, http://www.nat-hazards-earth-syst-sci.net/13/1827/2013/doi:10.5194/nhess-13-1827-2013, 2013.

Haresign, E., and Warren, C. R.: Melt rates at calving termini: a study at Glaciar León, Chilean Patagonia, Geological Society, London, Special Publications, 242, 99–109, http://dx.doi.org/10.1144/GSL.SP.2005.242.01.09, 2005.

Heller, V., Hager, W. H., Minor, H. E.: Landslide Generated Impulse Waves in Reservoirs, Zurich: Mitteilungen Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich, 2019.

Huggel, C., Kääb, A., Haeberli, W., Haeberli, W., Teysseire, P., and Paul, F.: Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps, Can. Geotech. J., 39, 316–330, http://dx.doi.org/10.1139/t01-099, 2002.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., and Kääb, A.: Accelerated global glacier mass loss in the early twenty-first century, Nature, 592, 726–731, https://doi.org/10.1038/s41586-021-03436-z, 2021.

Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., and Medeu, A.: Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling, Nat. Hazard Earth Syst. Sci., 17, 1837–1856, https://doi.org/10.5194/nhess-17-1837-2017, 2017.

Khanal, N. R., Hu, J. M., and Mool, P.: Glacial lake outburst flood risk in the Poiqu/Bhote Koshi/Sun Koshi river basin in the Central Himalayas, Mt. Res. Dev., 35, 351–364, http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00009, 2015.

Kougkoulos, I., Cook, S. J., Edwards, L. A., Clarke, L. J., Symeonakis, E., Dortch, J. M., and Nesbitt, K.: Modelling glacial lake outburst flood impacts in the Bolivian Andes, Nat. Hazard, 94, 1415–1438, https://doi.org/10.1007/s11069-018-3486-6, 2018.

Li, D., Shangguan, D. H, Wang, X., Ding, Y. J., Su, P. C., Liu, R. L., and Wang, M. X.: Expansion and hazard risk assessment of glacial lake Jialong Co in the central Himalayas by using an unmanned surface vessel and remote sensing, Sci. Total Environ., 784, https://doi.org/10.1016/j.scitotenv.2021.147249, 2021.

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F., and Allen, S.: Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya—Karakoram region, Ann. Glaciol., 57, 119–130, http://dx.doi.org/10.3189/2016AoG71A627, 2016.

Liu, Q., Mayer, C., Wang, X., Nie, Y., Wu, K. P., Wei, J. F., and Liu, S. Y.: Interannual flow dynamics driven by frontal retreat of a lake-terminating glacier in the Chinese Central Himalaya, Earth Planet. Sci. Lett., 546, 116450, https://doi.org/10.1016/j.epsl.2020.116450, 2020.

Lliboutry, L., Arnao, B. M., Pautre, A., and Schneider, B.: Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention, J. Glaciol., 18, 239–254, http://dx.doi.org/10.1017/S002214300002133X, 1977.

Loriaux, T., Casassa, G.: Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water storage in a sea-level rise context, Glob. Planet. Change, 102, 33–40, http://dx.doi.org/10.1016/j.gloplacha.2012.12.012, 2013.

Ma. J. S., Song. C. Q., Wang, Y. J.: Spatially and Temporally Resolved Monitoring of Glacial Lake Changes in Alps During the Recent Two Decades, Front. Earth Sci., 9, https://doi.org/10.3389/feart.2021.723386, 2021.

Mallalieu, J., Carrivick, J. L., Quincey, D. J., and Smith, M. W.: Calving seasonality associated with melt - undercutting and lake ice cover, Geophys. Res. Let., 47, e2019GL086561, https://doi.org/10.1029/2019GL086561, 2020.

Maurer, J. M., Schaefer, J. M., Russell, J. B., Rupper, S., Wangdi, N., Putnam, A. E., and Young, N.: Seismic observations, numerical modeling, and geomorphic analysis of a glacier lake outburst flood in the Himalayas, Sci. Adv., 6, eaba3645, http://dx.doi.org/10.1126/sciadv.aba3645, 2020.

Mergili, M., Fischer, J. T., Krenn, J., Pudasaini, S. P.: r. avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows, Geosci. Model Develop., 10, 553–569, http://dx.doi.org/10.5194/gmd-10-553-2017, 2017.

Mergili, M., Emmer, A., Juricova, A., Cochachin, A., Fischer, G. T., Huggel, C., and Pudasaini, S. P.: How well can we simulate complex hydro-geomorphic process chains? The 2012 multi-lake outburst flood in the Santa Cruz Valley (Cordillera Blanca, Peru), Earth Surf. Process. Landf., 431373–1389, http://dx.doi.org/10.1002/esp.4318, 2018.

Mergili M, Pudasaini SP, Emmer A, Fischer, G. T., Cochachin, A., Frey, H.: Reconstruction of the 1941 GLOF process chain at Lake Palcacocha (Cordillera Blanca, Peru), Hydrol. Earth Syst. Sci., 24, 93–114, https://doi.org/10.5194/hess-24-93-2020, 2020.

Miles, E. S., Watson, C. S., Brun, F., Berthier, E., Esteves, M., Quincey, D. J., Miles, K. E., Hubbard, B., and Wagnon, P.: Glacial and geomorphic effects of a supraglacial lake drainage and outburst event, Everest region, Nepal Himalaya, The Cryosphere, 12, 3891–3905, https://doi.org/10.5194/tc-12-3891-2018, 2018.

Muñoz, R, Huggel, C., Frey, H., Cochachin, A., and Haeberli, W.: Glacial lake depth and volume estimation based on a large bathymetric dataset from the Cordillera Blanca, Peru, Earth Surf. Process. Landf., http://dx.doi.org/10.1002/esp.4826, 2020.

Nie, Y., Liu, Q., Wang, J. D., Zhang, Y. L., Sheng, Y. W., and Liu, S. Y.: An inventory of historical glacial lake outburst floods in the Himalayas based on remote sensing observations and geomorphological analysis, Geomorphology, 308, 91–106, https://doi.org/10.1016/j.geomorph.2018.02.002, 2018.

Nie, Y., Liu, W., Liu, Q., Hu, X., and Westoby, M. J.: Reconstructing the Chongbaxia Tsho glacial lake outburst flood in the Eastern Himalaya: Evolution, process and impacts, Geomorphology, 370, 107393, https://doi.org/10.1016/j.geomorph.2020.107393, 2020.

O'Connor, J. E., Hardison III, J. H., Costa, J. E.: Debris Flows from Failures of Neoglacial-Age Moraine Dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon, 105 pp, 2001.

Osti, R., and Egashira, S.: Hydrodynamic characteristics of the Tam Pokhari glacial lake outburst flood in the Mt. Everest region, Nepal, Hydrol. Process., 23, 2943–2955, http://dx.doi.org/10.1002/hyp.7405, 2009.

Patel, L. K., Sharma, P., Laluraj, C. M., Thamban, M., Singh, A., and Ravindra, R.: A geospatial analysis of Samudra Tapu and Gepang Gath glacial lakes in the Chandra Basin, Western Himalaya, Nat. Hazard, 86, 1275–1290, https://link.springer.com/article/10.1007/s11069-017-2743-4, 2017.

Petrov, M. A., Sabitov, T. Y., Tomashevskaya, I. G., Glazirin, G. E., Chernomorets, S. S., Savernyuk, E. A., Tutubalina, O. V., Petrakov, D. A., Sokolov, L. S., Dokukin, M. D., Mountrakis, G., Ruiz-Villanueva, V., and Stoffel, M.: Glacial lake inventory and lake outburst potential in Uzbekistan, Sci. Total Environ., 592, 228–242, http://dx.doi.org/10.1016/j.scitotenv.2017.03.068, 2017.

Richardson, S. D., Reynolds, J. M.: An overview of glacial hazards in the Himalayas, Quat. Int., 65–6, 31–47, http://dx.doi.org/10.1016/S1040-6182(99)00035-X, 2000.

Sakai, A.: Glacial lakes in the Himalayas: a review on formation and expansion processes, Glob. Environ. Res., 16, 23–30, 2012.

Sattar, A., Haritashya, U. K., Kargel, J. S., Leonard, G. J., Shugar, D. H., and Chase, D. V.: Modeling lake outburst and downstream hazard assessment of the Lower Barun Glacial Lake, Nepal Himalaya, J. Hydrol., 598, 126208. https://doi.org/10.1016/j.jhydrol.2021.126208, 2021.

Schneider, D., Huggel, C., Cochachin, A., Guillén, S., and García, J.: Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru, Adv. Geosci., 35, 145–155, http://dx.doi.org/10.5194/adgeo-35-145-2014, 2014.

Sharma, R. K., Pradhan, P., Sharma, N. P., and Shrestha, D. G.: Remote sensing and in situ-based assessment of rapidly growing South Lhonak glacial lake in eastern Himalaya, India, Nat. Hazard, 93, 393–409, https://doi.org/10.1007/s11069-018-3305-0, 2018.

Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., and Strattman, K.: Rapid worldwide growth of glacial lakes since 1990, Nat. Clim. Change, 10, 939–945, https://doi.org/10.1038/s41558-020-0855-4, 2020.

Somos-Valenzuela, M. A., McKinney, D. C., Byers, A. C., Rounce, D. R., Portocarrero, C., and Lamsal, D.: Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal, Hydrol. Earth Syst. Sci., 19, 1401–1412, http://dx.doi.org/10.5194/hess-19-1401-2015, 2015.

Sugiyama, S., Skvarca, P., Naito, N., Enomoto, H., Tsutaki, S., Tone,K., Marinsek, S., and Aniya, M.: Ice speed of a calving glacier modulated by small fluctuations in basal water pressure, Nat. Geosci., 4, 597–600, http://dx.doi.org/10.1038/ngeo1218, 2011.

Sugiyama, S., Minowa, M., Sakakibara, D., Skvarca, P., Sawagaki, T., Ohashi, Y., Naito, N., and Chikita, K.: Thermal structure of proglacial lakes in Patagonia, J. Geophys. Res.: Earth Surf., 121, 2270–2286, http://dx.doi.org/10.1002/2016JF004084, 2016.

Sugiyama, S., Minowa, M., and Schaefer, M.: Underwater ice terrace observed at the front of Glaciar Grey, a freshwater calving glacier in Patagonia, Geophys. Res. Let., 46, 2602–2609, http://dx.doi.org/10.1029/2018GL081441, 2019.

Sugiyama, S., Minowa, M., Fukamachi, Y., Hata, S., Yamamoto, Y., Sauter, T., Schneider, C., and Schaefer, M.: Subglacial discharge controls seasonal variations in the thermal structure of a glacial lake in Patagonia, Nat. Commun., 12, 1–9, https://doi.org/10.1038/s41467-021-26578-0, 2021.

Sutherland, J. L., Carrivick, J. L., Gandy, N., Shulmeister, J., Quincey, D. J., and Cornford, S. L.: Proglacial lakes control glacier geometry and behavior during recession, Geophys. Res. Let., 47, e2020GL088865, https://doi.org/10.1029/2020GL088865, 2020.

Veh, G., Korup, O., and Walz, A.: Hazard from Himalayan glacier lake outburst floods, PNAS, 117, 907–912, https://www.pnas.org/cgi/doi/10.1073/pnas.1914898117, 2020.

Wang, X., Liu, S. Y., Ding, Y. J., Guo, W. Q., Jiang, Z. L., Lin, J., and Han, Y.: An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data, Nat. Hazard Earth Syst. Sci., 12, 3109–3122, http://dx.doi.org/10.5194/nhess-12-3109-2012, 2012.

Wang, X., Guo, X. Y., Yang C. D., Liu, Q. H., Wei, J. F., Zhang, Y., Liu, S. Y., Zhang, Y. L., Jiang, Z. L., and Tang, Z. G.: Glacial lake inventory of high-mountain Asia in 1990 and 2018 derived from Landsat images, Earth Syst. Sci. Data, 12, 2169–2182, https://doi.org/10.5194/essd-12-2169-2020, 2020.

Wang, W. C., Gao, Y., Anacona, P. I., Lei, Y. B., Xiang, Y., Zhang, G. Q., Li, S. H., and Lu, A. X.: Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalayas, Geomorphology, 306, 292–305, http://dx.doi.org/10.1016/j.geomorph.2015.08.013, 2018.

Watson, C. S., Quincey, D. J., Carrivick, J. L., Smith, M. W., Rowan, A. V., and Richardson, R.: Heterogeneous water storage and thermal regime of supraglacial ponds on debris-covered glaciers, Earth Surf. Process. Landf., 43, 229–241, http://dx.doi.org/10.1002/esp.4236, 2018.

Wei, J. F, Liu, S. Y., Wang, X., Zhang, Y., Jiang, Z. L., Wu, K. P., Zhang, Z., and Zhang, T.: Longbasaba Glacier recession and contribution to its proglacial lake volume between 1988 and 2018, J. Glaciol., 67, 473–484, https://doi.org/10.1017/jog.2020.119, 2021.

Westoby, M. J., Glasser, N. F., Brasington, J., Hambrey, M. J., Quincey, D. J., and Reynolds, J. M.: Modelling outburst floods from moraine-dammed glacial lakes, Earth-Sci. Rev., 134, 137–159, http://dx.doi.org/10.1016/j.earscirev.2014.03.009, 2014.

Wood, J. L., Harrison, S., Wilson, R., Emmer, A., Yarleque, C., Glasser, N. F., Torres, J. C., Caballero, A., Araujo, J., Bennett, G. L., Diaz-Moreno, A., Garay, D., Jara, H., Poma, C., Reynolds, J. M., Riveros, C. A., Romero, E., Shannon, S., Tinoco, T., Turpo, E., and Villafane, H.: Contemporary glacial lakes in the Peruvian Andes, Glob. Planet. Change, 204, 103574, https://doi.org/10.1016/j.gloplacha.2021.103574, 2021.

Yao, T. D., Thompson, L., Yang, W., Yu, W. S., Gao, Y., Guo, X. J., Yang, X. X., Duan, K. Q., Zhao, H. B., Xu, B. Q., Pu, J. C., Lu, A. X., Xiang, Y., Kalltel, D. B., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Change, 2, 663–667, http://www.nature.com/doifinder/10.1038/nclimate1580, 2012.

Yao, T. D., Xue, Y. K., Chen, D. L., Chen, F. H., Thompson, L., Cui, P., Koike, T., K.-M. Lau, W., Lettenmaier, D., Mosbrugger, V., Zhang, R. H., Xu, B. Q., Dozier, J., Gillespie, T., Gu, Y., Kang, S. C., Piao, S. L., Sugimoto, S., Ueno, K., Wang, L., Wang, W. C., Zhang, F., Sheng, Y. W., Guo, W. D., Ailikun, Yang, X. X., Ma, Y. M., Shen, S. S. P., Su, Z. B., Chen, F., Liang, S. L., Liu, Y. M., Singh, V. P., Yang, K., Yang, D. Q., Zhao, X. Q., Qian, Y., Zhang, Y., and Li, Q.: Recent third pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: Multidisciplinary approach with observations, modeling, and analysis, B. Am. Meteorol. Soc., 100, 423–444, https://doi.org/10.1175/BAMS-D-17-0057.1, 2019.

Yao, X. J., Liu, S. Y., Sun, M. P., Wei, J. F., and Guo, W. Q.: Volume calculation and analysis of the changes in moraine-dammed lakes in the north Himalaya: a case study of Longbasaba lake, J. Glaciol., 58, 753–760, http://dx.doi.org/10.3189/2012JoG11J048, 2012.

Yao, X. J., Liu, S. Y., Han, L., Sun, M. P., and Zhao, L. L.: Definition and classification system of glacial lake for inventory and hazards study, J. Geogr. Sci., 28, 193–205, https://doi.org/10.1007/s11442-018-1467-z, 2018.

Zemp, M., Huss, M., Thibert, E., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., and Cogley, J. G.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016, Nature, 568, 382–386, https://doi.org/10.1038/s41586-019-1071-0, 2019.

Zhang, G. Q., Yao, T. D., Xie, H. J., Wang, W. C., and Yang, Wei.: An inventory of glacial lakes in the Third Pole region and their changes in response to global warming, Glob. Planet. Change, 131, 148–157,

https://doi.org/10.5194/tc-2023-12
Preprint. Discussion started: 21 February 2023

http://dx.doi.org/10.1016/j.gloplacha.2015.05.013, 2015.

Zhang, T. G., Wang, W. C., Gao, T. G., and An, B. S.: Simulation and Assessment of Future Glacial Lake Outburst Floods in the Poiqu River Basin, Central Himalayas, Water, 13, https://doi.org/10.3390/w13101376, 2021.

Zhang, T. G., Wang, W. C., An, B. S., Gao, T. G., and Yao, T. D.: Ice thickness and morphological analysis reveal the future glacial lake distribution and formation probability in the Tibetan Plateau and its surroundings, Glob. Planet. Change, 216, 103923, https://doi.org/10.1016/j.gloplacha.2022.103923, 2022.

Zheng, G. X., Mergili, M., Emmer, A., Allen, S., Bao, A. M., Guo, H., and Stoffel, M.: The 2020 glacial lake outburst flood at Jinwuco, Tibet: causes, impacts, and implications for hazard and risk assessment, The Cryosphere, 15, 3159–3180, https://doi.org/10.5194/tc-15-3159-2021, 2021.