Reviewer 3#

This study presents the approach of geometrical approximation of glacial lake bathymetry, considering different types of glacial lakes. I'm convinced that this might be an important contribution towards filling apparent research gap and addressing the need for lake bathymetries in GLOF and lake evolution studies. I have two major and a couple of minor concerns regarding this study.

Reply: Thank you for acknowledging the significance of our study. By considering both general and specific comments from three reviewers, we have undertaken a major revision of this manuscript to enhance the clarity of language and to improve the quality of figures. Below are our point-to-point responses. Reviewers' comments are in black font, while our response in blue font.

My first concern is associated with the novelty methodological aspects of this study. Please correct me if I'm wrong, but from reading your manuscript, my feeling about your methodology is that:

- You approximate the max. lake depth from empirical equations
- You place this deepest point in the middle of the lake polygon
- You interpolate the rest of the lake basin (with possible use of different curves such as straight, parabola or ellipsoid)

According to my knowledge, various GIS software offer different interpolation tools too. Could you please explain and highlight the advantage and novelty of your approach? This is especially important considering that your code is only provided on request.

Reply: Thank you very much for your comment.

(Section2.3, P6L137-157) For periglacial, extraglacial, and supraglacial lakes, we identified four standard conceptual models (SCMs) for each glacial lake types: 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). Their maximum water depths were set in the center lake. Furthermore, we considered the SCMs of proglacial lakes to be half of the preceding four SCMs, namely the semi-hemisphere structured by the elliptical side ($V = 1/3AD$); the semi-hemisphere structured by the upward-opening parabolic side ($V = 1/4AD$); semi–cone structured by the straight side ($V = 1/6AD$); and the semi-cone structured by the rightward-opening parabolic side ($V = 1/10AD$). We also designed two SCMs for the ice-dammed lake (Fig. 3a): the semi–cone structured by the straight side and the triangular cone ($V = 1/3A \cdot D$). The deepest point for proglacial and ice-dammed lake are set near the glacier-lake interface.

The advantage and novelty of the study is that we present the standard conceptual models for each type of glacial lake and demonstrate a procedure to identify the most compatible general conceptual model for a specific glacial lake by equalizing the volume of GCM with actual lake volume. To our knowledge, this is the first model to simulate the bathymetric distribution of glacier lakes at present. We have considered different types of glacial lakes and performed geometric approximations to the shapes of glacial lake basins. These scientifically assumptions cannot be achieved by different interpolation tools in various GIS software.

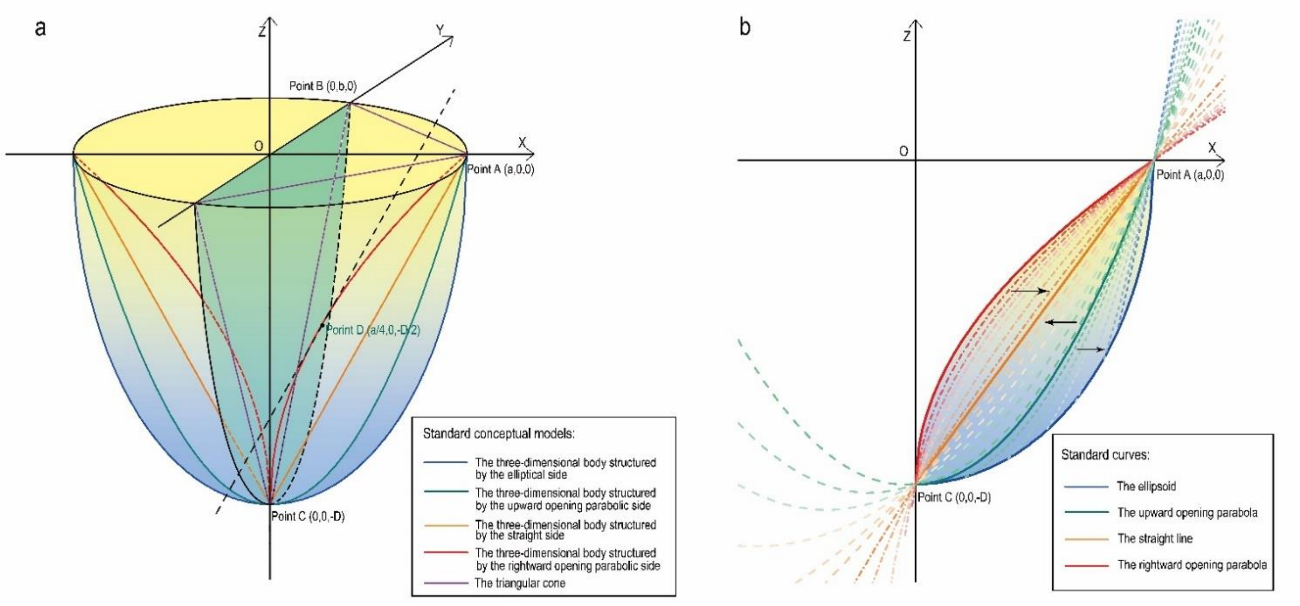


Figure 3. (a) Schematic diagram illustrates the shapes of the SCMs, namely the hemisphere structured by the elliptical side/upward-opening parabolic side, the cone structured by the straight side/rightward-opening parabolic side, the triangular cone, as well as their shapes when symmetrically divided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

My second concern is associated with the validation procedure of this approach. The authors compile global bathymetric dataset and claim that their method could be applied around the globe (L320). However, only three lakes with very similar characteristics (all moraine-dammed, all large, all from Himalaya) are used for the validation. More experiments are needed to evaluate the performance of your approach considering: (i) different lake types; (ii) different lake sizes; (iii) different geographical contexts.

Reply: (Section 2.6, P12L232-245) Thank you very much for the suggestion. The original glacial lakes utilized to exhibit and validate results were extended from three to six (Table 2). Six sets of bathymetry data were collected for the typical glacial lakes in the Himalayas and Nyainqentanglha (Fig. 6). Among them, Cirenmaco, Jialongco, Poiqu NO.1, and Maqiongco were classified as periglacial lakes, while the Longbasaba Lake and Dasuopuco were classified as proglacial lakes. The expansion of samples allows us to evaluate the performance of our conceptual models across different types, sizes, and geographic locations of glacial lakes.

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

Name	Lat°	Lon°	Region	Topological position	Survey year	Area (km^2)	Volume (10^6 m^3)	Mean water depth (m)	Maximum water depth (m)	Semi-long axis (m)	Semi-minor axis (m)
Jialongco	28.21	85.85	Central Himalaya	periglacial	2020	0.61	37.5	58.2	133	757	314
Cirenmaco	28.07	86.07	Central Himalaya	periglacial	2012	0.33	18.0	55	115	549	185
Poiqu NO.1	28.14	85.92	Central Himalaya	periglacial	2021	0.11	2.7	25.5	75.1	242	129
Maqiongco	30.49	93.36	Nyainqentanglha	periglacial	2021	0.23	3.2	15	33.5	493	168
Longbasaba Lake	27.95	88.08	Eastern Himalaya	proglacial	2009	1.17	64.0	48	102	1949	319
Dasuopuco	28.44	85.78	Central Himalaya	proglacial	2021	0.55	0.55	33.8	93	1362	247

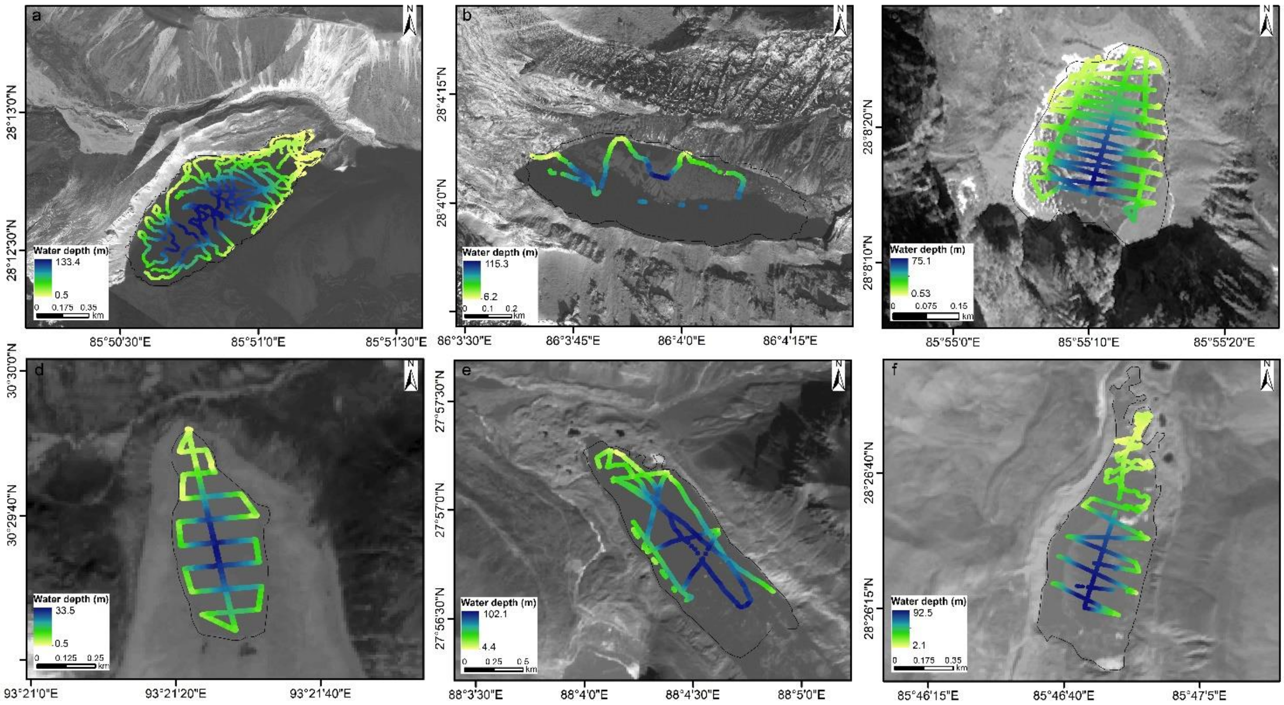


Figure 6. The water depth observed along the bathymetric routes for (a) Jialongco, (b) Cirenmaco, (c) Poiqu NO.1, (d) Maqiongco, (e) Longbasaba Lake, and (f) Dasuopuco.

(Section4.2, P17L311-326) Our modeling theory is based on the observations of glacial lake bathymetric distribution characteristics worldwide, revealing a universal geometrical approximation law for glacial lake bathymetry. Therefore, this modeling approach may be applicable to most glacial lakes in mountain glaciers. However, it is strictly limited by several constraints. Firstly, the designed conceptual model is more suitable for those glacial lakes with typically lengthy and elliptical-like shapes, and may be less applicable to very irregularly shaped glacial lakes, such as the ice-marginal and thermokarst lakes in the Greenland and Alaska region (Field et al., 2021; Coulombe et al., 2022). Similarly, we did not collect any glacial lake bathymetry data in polar regions which causes non-applicability on supraglacial lakes over the Greenland/Antarctic Ice sheets. Secondly, the parent glacier can be a cirque-valley glacier or a small/medium sized valley glacier flowing along a straight valley, ensuring idealized formation conditions for the glacial lake basin with minimal erosion and deposition from tributaries.

Although the simulated results were only validated in the periglacial and proglacial lakes of the Himalayas and Nyainqentanglha due to limited observation data, the comparison results of the measured and modeled depth values at different locations of the six glacial lakes demonstrates the rationality and reliability of our conceptual models. Between the estimated and measured water depths along the bathymetric routes, the average deviation, mean absolute deviation, and mean root square error for the six glacial lakes all described good consistency. Neither near the lakeshore nor the lake center do the estimates show intolerable dispersions (Figure 7 and 8).

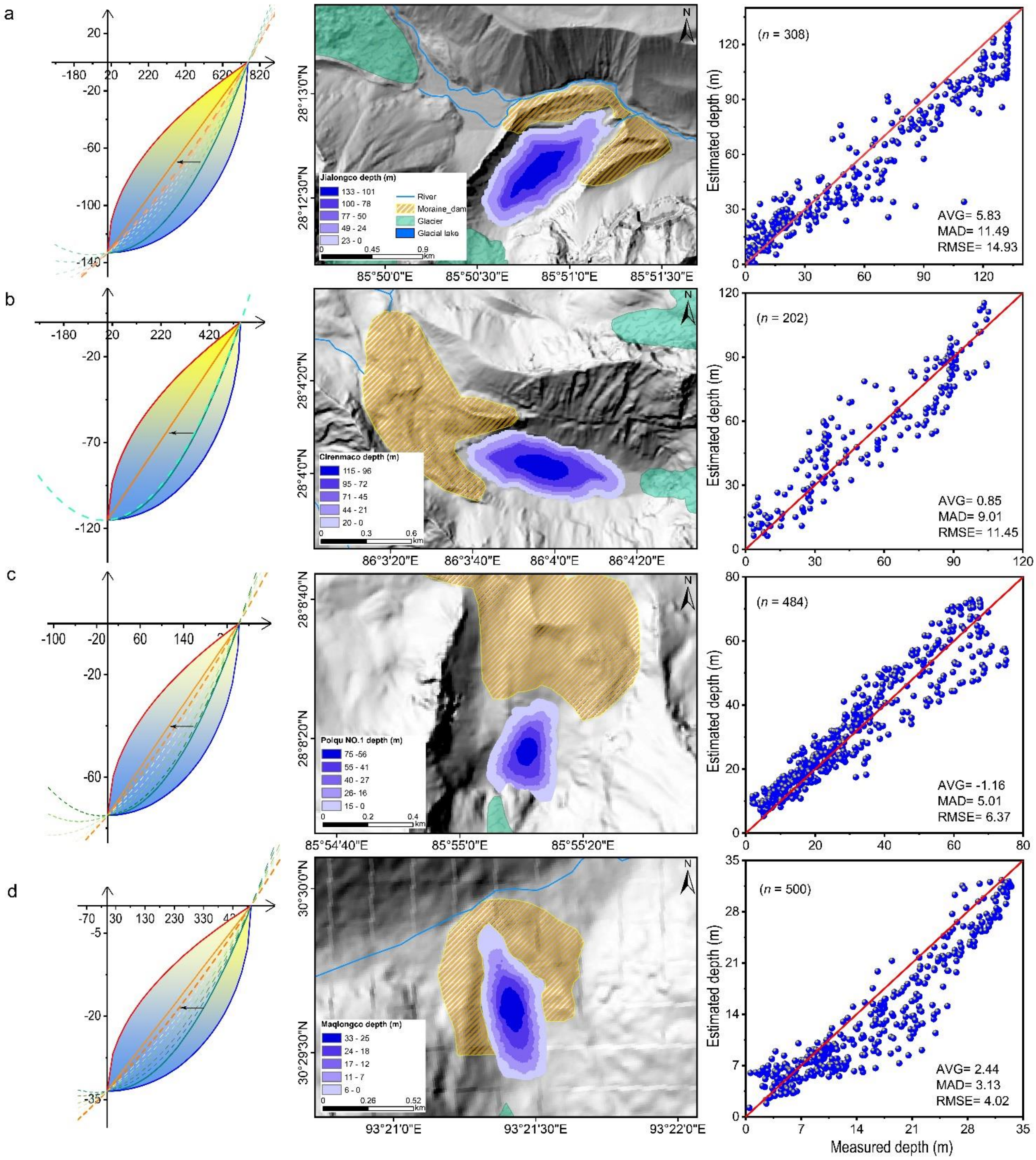


Figure 7. Modeled glacial lake bathymetric distributions of the four selected periglacial lakes. (a) Jialongco, (b) Cirenmaco, (c) Poiqu NO.1, and (d) Maqiongco. The average deviation (AVG), mean absolute deviation (MAD), and root mean square error (RMSE) were selected to depict the consistency between 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.

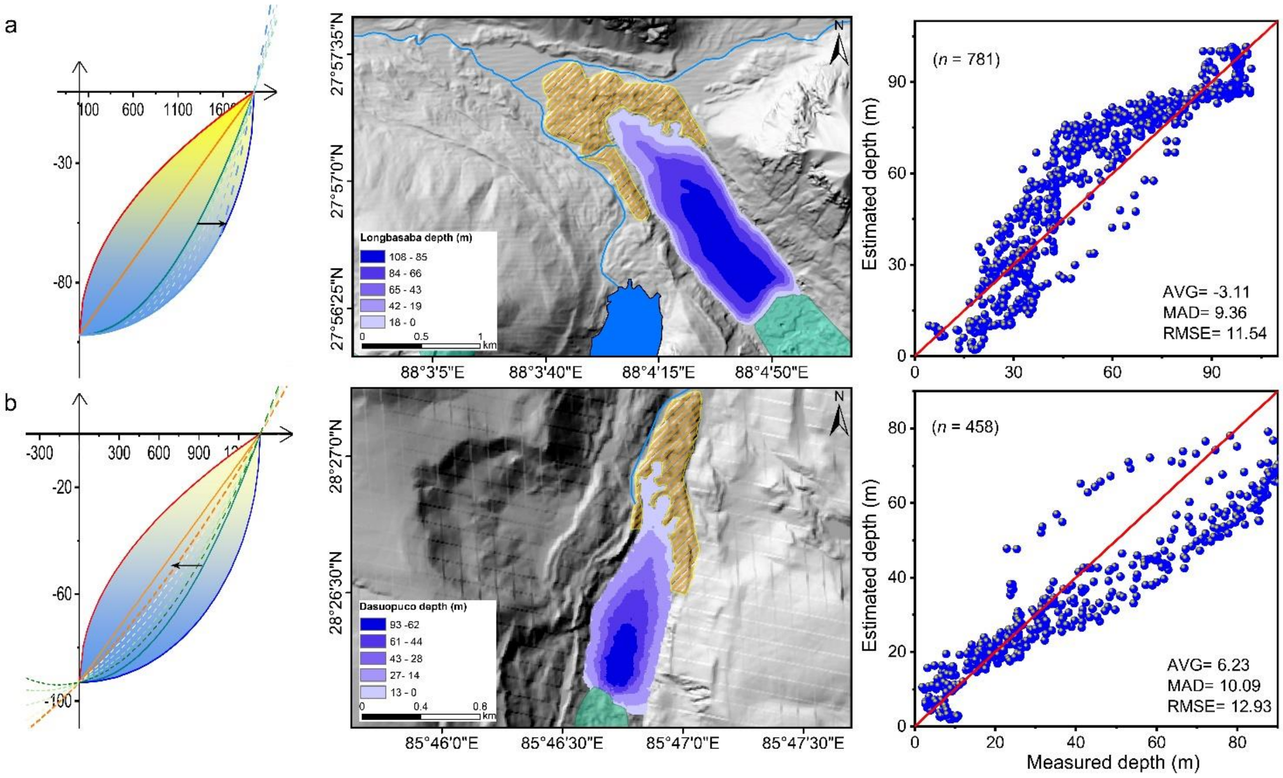


Figure 8. Modeled glacial lake bathymetric distributions of the two selected proglacial lakes. (a) Longbasaba Lake, and (b)Dasuopuco. The average deviation (AVG), mean absolute deviation (MAD), and root mean square error (RMSE) were selected to depict the consistency between the simulated and measured individual water depths along the boat routes. The movements of the general curves from one standard curve to another are also indicated.

Personally, I would very much appreciate distinguishing between moraine- and bedrock-dammed lakes, because while a bedrock-dammed lake is the one that occupies a depression carved in a bedrock by a glacier, a moraine-dammed lake is trapped behind a wall of material deposited by a glacier – and so the bathymetries of those two types are likely to be different (as e.g. Muñoz et al., 2020 dataset from Peru confirms). This could actually help you to solve the problem with low R^2 values of so called extraglacial lakes.

Reply: Thank you for the constructive comments. Our studies are not aimed at fitting empirical formulas with regional or global applicability, but rather at simulating the bathymetric distribution of glacial lakes. Certainly, accurate estimation of the volume and maximum depth of a specific glacial lake is crucial for our modeling work. Therefore, we have conducted a discussion of the existing empirical formulas related to glacial lakes, not limiting ourselves to bedrock-dammed lakes only.

(Section 4.3, P18L348-369) Currently, many studies have attempted to fit V-A equations with regional or claimed global applicability for various types of glacial lakes (Cook et al., 2015; Qi et al., 2022). The most common classification method for glacial lakes is based on dam materials, such as moraine-dammed, bedrock-dammed, and landslide-dammed. However, this study reveals that the different types of glacial lakes have different ideal basin shapes that may be unfavorable to most already formed V-A empirical formulations, although some have high R^2 (Table 1). For instance, most of the proglacial and periglacial lakes is generally dammed by moraine, involving in many fitting works of V-A relationships. Unreasonably, the incompletely developed basins of proglacial lakes and the fully developed basins of periglacial lakes are often described by same empirical formulas (Fig. 9a), disregarding the distinct basin development stages between them. This aspect has overlooked in the previous studies. In our fitted curves of V-A relationships for various types of glacial lakes (Fig. 4), the V-A relationship for proglacial lakes is robust, indicating global applicability. However, the V-A relationships for periglacial and extraglacial lakes exhibit many outliers, suggesting a stronger influence from exogenous materials for these based on our hypothesis. The V-A relationships of these glacial lakes decoupled with their glaciers at least require parameters related to the glacier characteristics and time of detachment for further description.

There is no single classification method can adequately capture the refined characteristics of glacial lakes. Even lakes classified as the same type may differ in terms of parent glaciers, bedrock properties, or dam materials. In the modeling of glacial lake bathymetric distribution, accurately estimating the total volume and maximum water depth of glacial lakes is crucial. Therefore, future studies should not only focus on whether the empirical formula is generalizability or global applicability, but also develop more detailed classification criteria for glacial lakes, comprehensively considering dam materials, topological positions, glacier properties, area intervals, geographic location, and other relevant factors. This will facilitate a well-fitting of regional empirical relationships of V-A and D-A for various types of glacial lakes, thereby reducing the dispersion between data points.

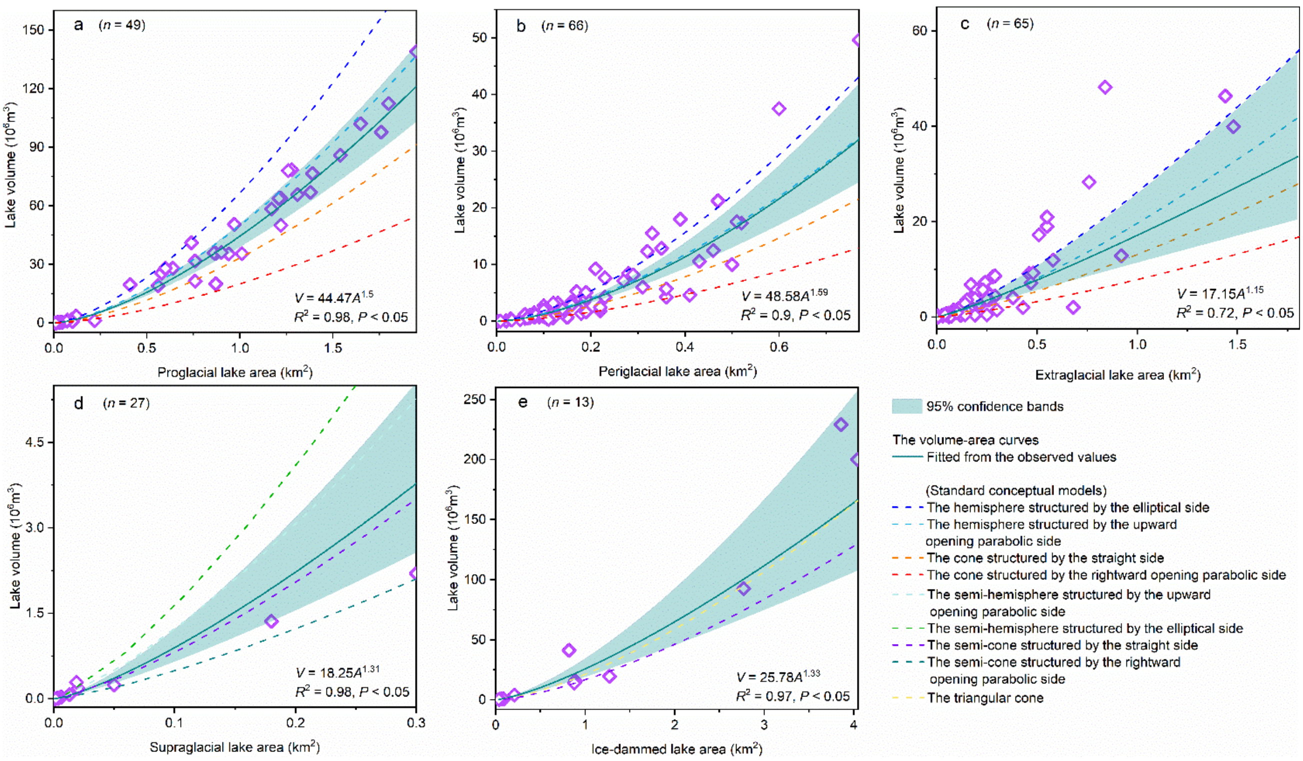
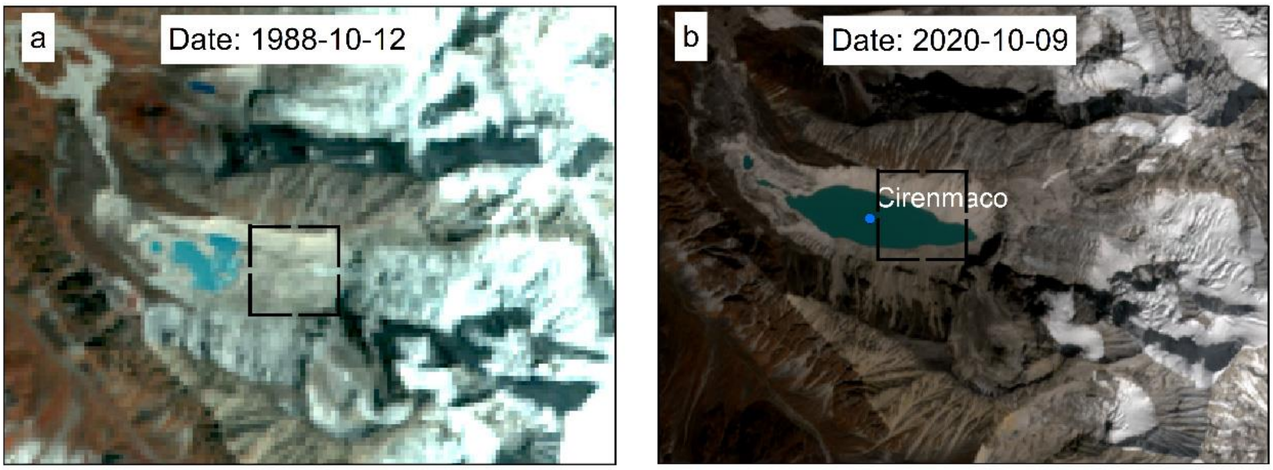


Figure 4. Relationships between the volume (V) and area (A) of glacial lakes were compiled in the present study for the following lake types: (a) proglacial lake, (b) periglacial lake, (c) extraglacial lake, (d) supraglacial lake, and (e) ice-dammed lake.

L26: I would not call your three lakes typical, also because two of them produced a GLOF in the past, decreasing ‘natural’ lake water level; this further undermines the validation (see my general comment)

Reply: See our reply to the general comment. We have expanded the validation samples to six glacial lakes representing different types, sizes, and geographic locations. Your concern is reasonable. However, the previously outburst glacial lakes can also be used to validate. Take Cirenmaco as an example, it was originally an incompletely developed moraine-dammed lake prior to the 1981 GLOF, and its shape is quite different from that of a fully developed glacial lake in 2020. However, what matters is that the drainage of the lake did not cause substantial damage to the moraine dam, indicating the integrity of the lake basin. The same situation applies to Jialongco.



L41: when talking about these 50%, please mention that this only applies to glacial lakes located within 1km buffer from the RGI glaciers; overall regional figures differ substantially.

Reply: (Section 1, P2L38) This error has been corrected in the revised manuscript.

L46: you might want to refer to the latest GLOF inventory compiled by Lützow et al: https://essd.copernicus.org/preprints/essd-2022-449/

Reply: (Section 1, P2L43) Thank you for the information. The recommended reference was appropriately cited in the revised manuscript.

L51: attenuates instead of proceeds?

Reply: (Section 1, P2L48) This error has been corrected.

L60: Tibetan Plateau and the Himalayas are different regions.

Reply: (Section 1, P2L56) The term "Third Pole" was used throughout the manuscript to clarify the geography of Tibetan Plateau and adjacent mountain regions.

L76: if you mention 'several studies', you should refer to more than just one study

Reply: (Section 1, P3L70). We have added two new references here:

Zhang, G. Q., Bolch, T., Yao, T. D., Rounce, D.R., Chen, W. F., Veh, G., King, O., Allen, S.K., Wang, M. and Wang, W. C. Underestimated mass loss from lake-terminating glaciers in the greater Himalaya, Nat. Geosci., 16, 1–6. https://doi.org/10.1038/s41561-023-01150-

1, 2023.

Watson, C. S., Kargel, J. S., Shugar, D. H., Haritashya, U. K., Schiassi, E., and Furfaro, R. Mass Loss From Calving in Himalayan Proglacial Lakes Front. Earth Sci. 7, 342, http://dx.doi.org/10.3389/feart.2019.00342, 2020.

L105: what about the location of this deepest point? I have not figured out how you treat this in your study? Is the maximum depth always placed in the lake center?

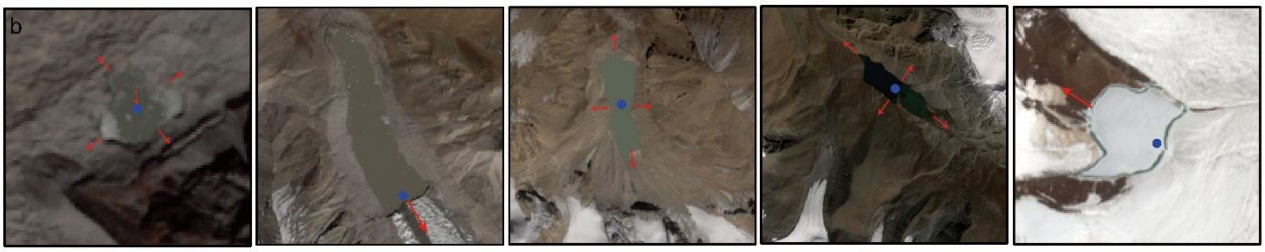
Reply: For periglacial, extraglacial, and supraglacial lakes, their maximum water depths were set in the center lake, while the deepest point for proglacial and ice-dammed lake were set near the glacier-lake interface.

L107: how do bathymetric data help to understand lake evolution (unless you have repeated bathymetric surveys)? Please clarify.

Reply: This sentence was revised as follows **(Section 2.2, P4L98)**: "We used the compiled glacial lake bathymetry data to fit the curves of V–A (glacial lake area) and D–A to understand the potential shapes of an idealized lake basin." In fact, this is connected to theoretical descriptions provided for the general formulas of V-A and D-A of glacial lakes in Section 2.3.

L109: please consider schematic figure of these different expansion mechanisms.

Reply: (Figure 1b) We have used the red arrows to indicate the possible main directions of expansion of the glacial lake.



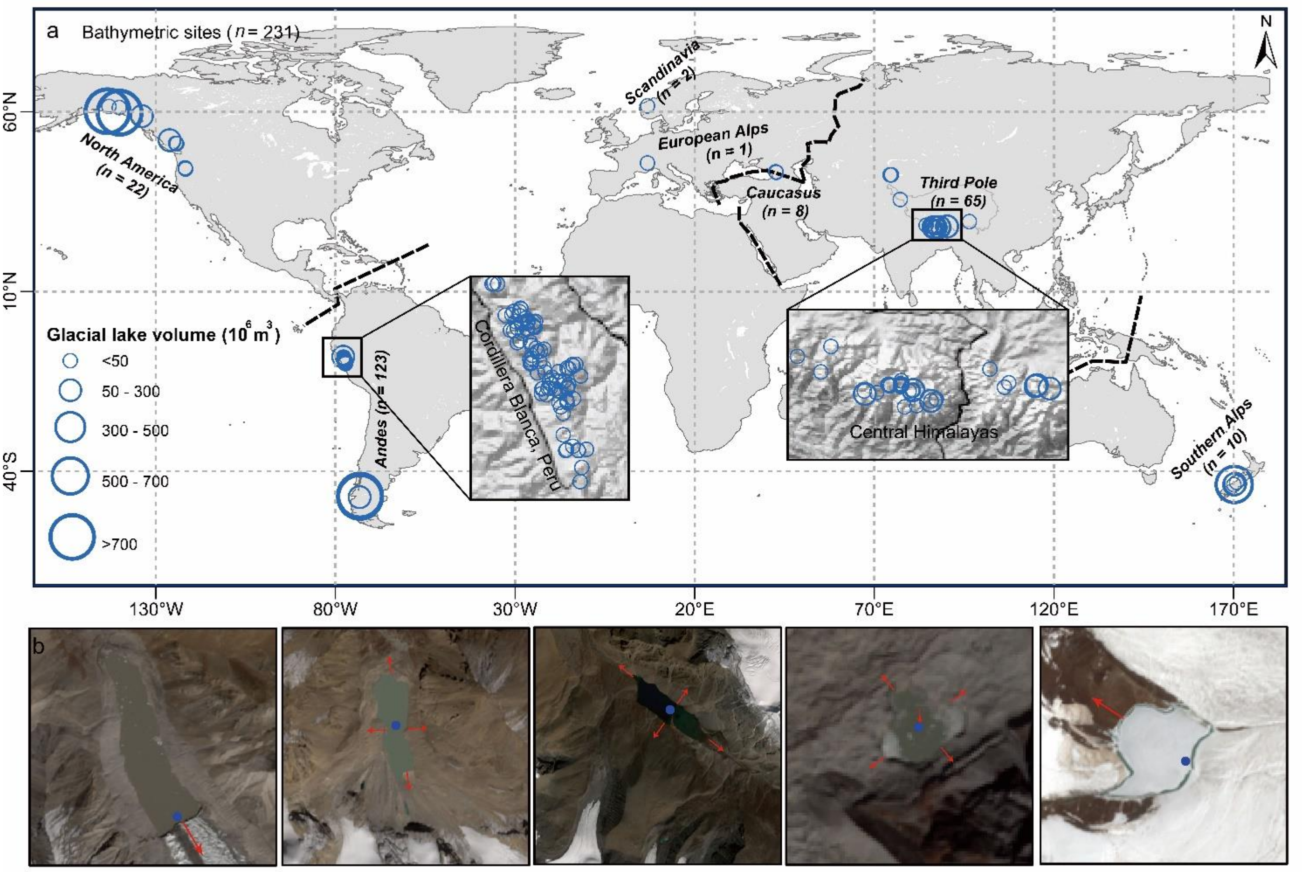
Supraglacial lake Proglacial lake Periglacial lake Extraglacial lake Ice-dammed lake

L116-120: I don't understand why/how is this relevant for the rest of the study? The key for the bathymetry of periglacial lake is what morphological glacial lake type it is (bedrock- vs. moraine-dammed) rather than how the lake water level possibly changes with precipitation or meltwater input? Or maybe I'm just missing your point here.

Reply: (Section 2.2, P4L104-111) We assumed that different types of glacial lakes have different expansion mechanisms and, thus, different conceptual models. 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 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, thereby potentially expanding in all horizontal directions. The proglacial lake's expansion mainly proceeds backward by glacial retreat. 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.

Figure 1: please consider changing the visualization in a way it is recognizable how many bathymetries you compiled from individual regions.

Reply: (Section 2.2, P5L112) See our updated figure below:



Proglacial lake Periglacial lake Extraglacial lake Supraglacial lake Ice-dammed lake

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 (formed when glacier surges block downstream valleys or meltwater fills depressions between retreating tributary and main glaciers). Red arrows indicate the possible main directions of expansion of the glacial lake, and the blue points represent the location of maximum water depth.

L185-191: the difference between standard and generalized model is not clear.

Reply: This sentence was revised as follows **(Section 2.4, P9L178-193)**: If a specific glacial lake has determined its parameters such as surface size, maximum water depth, and volume, it is difficult that the closest SCM would accurately represent the most appropriate conceptual model. This is because the relatively inherent volume of the SCM is hardly equal to the volume of a specific glacial lake. In other word, the volume curve of the SCM is constant, and therefore, the volume point of a specific glacial lake may deviate from the SCM volume curve. Consequently, directly using the SCM to nest and interpolate a realistic glacial lake bathymetric distribution would result in an initial over- or underestimation of the total lake 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.

Figure 5: is the deepest point located always in the middle of the lake? Because many glacial lakes tend to be deepest in their rare part (beneath the icefalls where the erosion is the most intense)

Reply: See our reply previously.

L244: see my comment to L26.

Figure 6: in fact, you do not cover central part and half of the lake area for the Jialongco with your bathymetrical profiling; I'm not sure such data are suitable for the validation of the bathymetry approximation (a lot of interpolation had to be used, right?)

Reply: See our reply to general comment. The general conceptual model of this lake was derived based on its measured volume and maximum water depth. The exhibited water depth distribution is solely determined by the available observed data and the specific placement of bathymetric routes during that period. In essence, the consistency between our simulated and measured water depths under a given bathymetric condition serves as an indicator of the applicability of the conceptual model. If a more complete bathymetric route placement is performed, it is sufficient to recalculate its optimal general conceptual model and simulate the bathymetric distribution.

L265: relatively deep compared to what?

Reply: This sentence was revised as follows **(Section 3, P13L256)**: "The results reveal that the proglacial and periglacial lakes exhibit greater depths as their SCMs are closer to the hemisphere structured by the upward-opening parabolic side. Conversely, the SCMs of the extraglacial and supraglacial lakes are closer to the cone structured by the straight side, indicating relatively shallower depths."

L273: in the model description you talk about maximum depth but here about the mean depth, this is bit confusing.

Figure 7: is this validation done against really measured points only or against interpolated points too?

Reply: (Section 2.6, P12L243) The six 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 and the overall parameters (total volume and mean water depth) to verify the feasibility and accuracy of our modeling method.

L310: please refer to a study supporting this assumption.

Reply: This is merely a conjecture we have made. Due to the constraints of our literature review, it has been challenging to find specific studies that directly support this assertion.

L318-L320: I would not agree that using the datapoints from around the globe will make your method globally-applicable; it may be the other way round too if you assume individual regions differ (and they do if you compare surrounding topography of glacial lakes in Tropical Andes and Southern Alps, for instance)

Reply: Thank you for the constructive comments. Additional constraints have been imposed on glacial lakes suitable for modeling bathymetric distribution, while ensuring the study maintains its broad applicability. We kindly request that the reviewers take into consideration our explanation provided below.

(Section 4.2, P17L312-328) Our modeling theory is based on the observations of glacial lake bathymetric distribution characteristics worldwide, revealing a universal geometrical approximation law for glacial lake bathymetry. Therefore, this modeling approach may be applicable to most glacial lakes in mountain glaciers. However, it is strictly limited by several constraints. Firstly, the designed conceptual model is more suitable for those glacial lakes with typically lengthy and elliptical-like shapes, and may be less applicable to very irregularly shaped glacial lakes, such as the ice-marginal and thermokarst lakes in the Greenland and Alaska region (Field et al., 2021; Coulombe et al., 2022). Similarly, we did not collect any glacial lake bathymetry data in polar regions which causes non-applicability on supraglacial lakes over the Greenland/Antarctic Ice sheets. Secondly, the parent glaciers of glacial lakes can be a cirque-valley glacier or a small/medium sized valley glacier flowing along a straight valley, ensuring idealized formation conditions for the glacial lake basin with minimal erosion and deposition from tributaries.

Although the simulated results were only validated in the periglacial and proglacial lakes of the Himalayas and Nyainqentanglha due to limited observation data. In the future, this method is still great potential for further validation in other regions of the world.

L324-329: please see my general comment about the validation.

Reply: See our reply to general comments.

L328: how did you come to this estimation? Please explain.

Reply: This sentence was deleted.

L334: do you mean outliers?

Reply: Yes

L358: there are other problems in predictive GLOF modelling that may introduce much higher uncertainty than simple empirical equations-derived volume, for instance dam breach scenarios (see e.g. https://doi.org/10.5194/nhess-22-3041-2022)

Reply: The recommended reference was appropriately cited.

L365: yes, and I'm sceptic to this 'worst case scenario' approach, because complete lake drainages are very rare (and should be only considered in well-justified cases) while incomplete drainages are much more common (https://doi.org/10.1016/j.gloplacha.2021.103722)

Reply: The recommended reference was appropriately cited.

L407: it is actually not clear to me how partly glacierized lake basins (i.e. proglacial lakes) are treated in your model?

Reply: (Section 2.3) For proglacial lakes, their standard conceptual models were designed as the semi-hemisphere structured by the elliptical side ($V = 1/3AD$); the semi-hemisphere structured by the upward-opening parabolic side ($V = 1/4AD$); semi–cone structured by the straight side ($V = 1/6AD$); and the semi-cone structured by the rightward-opening parabolic side ($V = 1/10AD$). The maximum water depth was set near the glacier-lake interface. Certainly, their standard elliptical surfaces were also sheared along the short axis and divided in half to accommodate the variations of the deepest location and glacial lake shape.