First Referees comments

Review: Predicting the Risk of Glacial Lake Outburst Floods in Karakorum

The authors of the article "Predicting the Risk of Glacial Lake Outburst Floods in Karakorum" turn to a very important topic, the investigation of the trigger mechanisms of GLOFs. The article contains interesting theories and examines intriguing relations in this context. The article is well written and for the most part logically structured. However, the flow of reading is sometimes impeded because paragraphs do not follow on logically from one another, especially in the methodological chapters 2.2-2.4. But there are also some backtracks later on when methods and contexts are explained instead of just presenting the results of the scientific work.

Thank you for noting that the manuscript is well written and indicating where some restructuring would benefit the flow of the argument.

In particular, the focus on determining the lake volume appears somewhat convoluted and, in some cases, does not refer enough to previous research. Hypotheses are put forward and rejected; it is not always clear what the added value is compared to previous methods (e.g. Cook and Quincy (2015) or the paper by Zhang et al. (2023) already mentioned in the comments). Chapter 3.1 on the relationship between water depth and GLOF event is more interesting and also more fluently written, to my mind.

Thank you for your valuable feedback. We have made significant revisions to address your concerns about the convoluted nature of the lake volume determination section and the need for better contextualization with previous research. The methodology section now provides a clearer, more logically organized account of our approach. We have added explicit references to Cook and Quincy (2015) and Zhang et al. (2023) to better situate our work within existing research and highlighted how our integration of high-resolution UAV data with historical remote sensing datasets offers improved accuracy in lake volume estimations, reducing uncertainties and enhancing GLOF event predictions.
The revised results section 3.1, now 4.1, titled "Surge Velocity and Ice Dam Volume," presents relationships and hypotheses more explicitly, with improved data presentation and detailed explanations to support our findings. This section maintains the fluency and clarity of Chapter 4.1, ensuring consistency throughout the manuscript. We believe these revisions address your concerns and significantly enhance the clarity, coherence, and scientific contribution of our work. Thank you again for your insightful comments.

Although the Discussion contains some parts that would have been better placed earlier in the manuscript as they contain new sources and information, it is well written and presents the results of the study, its limitations and achievements well and puts them in context with previous publications.

Thank you for your positive feedback on the Discussion section. Based on your suggestion, we have revised and updated it to ensure that all new sources and information are appropriately

integrated into earlier sections of the manuscript. This restructuring enhances the overall fluency and logical flow of the manuscript, making the narrative more cohesive. We are confident that these changes have improved the clarity and readability of our study. Thank you again for your valuable insights.

The illustrations support the article in the right places, but could benefit from a revision of the color schemes and, in some cases, a little more scientific clarity in the statements.

Illustrations have been resided in line with your suggestions.

Overall, the results are interesting and contribute to the current state of science, especially with regard to the relationship between lake depth, water pressure and the timing of a GLOF. With the editing of some minor revisions, I see no problems for publication and congratulate the authors on this work.

Thank you for your encouraging feedback and positive assessment of our work. We are pleased to hear that you find our results interesting and a valuable contribution to the current state of science, particularly regarding the relationship between lake depth, water pressure, and the timing of GLOF events. We appreciate your recognition of our efforts and are committed to addressing the minor revisions you have noted. We are confident that these final adjustments will further enhance the quality of our manuscript. Thank you once again for your constructive comments and support.

References:

Cook, S. J. and Quincey, D. J.: Estimating the volume of Alpine glacial lakes, Earth Surf. Dynam., 3, 559–575, https://doi.org/10.5194/esurf-3-559-2015, 2015.

Zhang, T., Wang, W., and An, B.: A conceptual model for glacial lake bathymetric distribution, The Cryosphere, 17, 5137–5154, https://doi.org/10.5194/tc-17-5137-2023, 2023.

Specific comments:

At the beginning of chapter 2, the authors mention three glaciers. At this point, the reader wonders: Why were these glaciers and their lakes selected? It would facilitate the flow of reading if the authors could explain this a bit at this point. Later, in P9L232, the authors mention, that “the three Karakorum [sic!] glaciers can be used as regional exemplars [sic!] of surge behavior controlling GLOF occurrence”. This is too late, this needs to be explained much earlier. Maybe the authors could add a short subchapter about the study area, indicating its location in HMA and the position of the individual glaciers?

An additional chapter (2) has been added to explain the context of choosing the three glaciers for investigation. The new Figure 1 provides an overview of the location of the three glaciers within High Mountain Asia.
“Study Area

The Karakoram Mountain ranges in HMA are known for their complex geology, climatic variability, and denudation processes, including debris flows, mudflows, landslides, rockfalls, avalanches, and GLOFs. As was noted in the preceding section, changes in glacier dynamics, increasing glacier surges, and a trend of increases in GLOF-related disasters characterize this region. These hazards are responsible for substantial economic losses, including the destruction of residences, infrastructure such as roads and bridges, and agricultural areas, as well as blockages of transportation routes like the Karakoram Highway and other expressways (Shrestha et al., 2023). Glacier surges in the region have been recorded since the 15th century (Bazai et al., 2021). Since the application of remote sensing to the monitoring of the glaciers from 1970 to 2020, an increasing occurrence of glacier surges has been recorded from the 1990s, with some glacier surges being linked to the formation of ice-dammed lakes and subsequent lake outburst floods. Some lakes persist only seasonally, forming in the winter when temperatures are very low and draining slowly in the spring or summer. Other lakes are more persistent (Bhambri et al., 2019; Hewitt and Liu, 2010), and pose the potential for catastrophic outbursts. The most frequent glacier surges and formation of lakes leading to outburst floods in the Karakoram region occur for the Khurdopin, Kyager, and Shishper glaciers. Although the foreland of the Kyager Glacier, situated in the Shaksgam Valley, is uninhabited, GLOFs have caused damage and losses further downstream. Conversely, GLOFs from the Khurdopin and Shishper glaciers, located in the densely populated Hunza area, have resulted in casualties and substantial economic losses. Consequently, these glaciers and their lakes are selected for study. The focus of the broader investigation is to obtain the data necessary to understand the complex behaviour of the glaciers and their drainage systems with a view to anticipating when the occurrence of GLOFs is imminent. Thus, there is an urgent need to identify trigger factors for GLOFs to provide downstream warnings in a timely fashion. A better understanding of the complex process behaviours should eventually lead to improved prediction of such events, not only within the Karakoram but also worldwide.

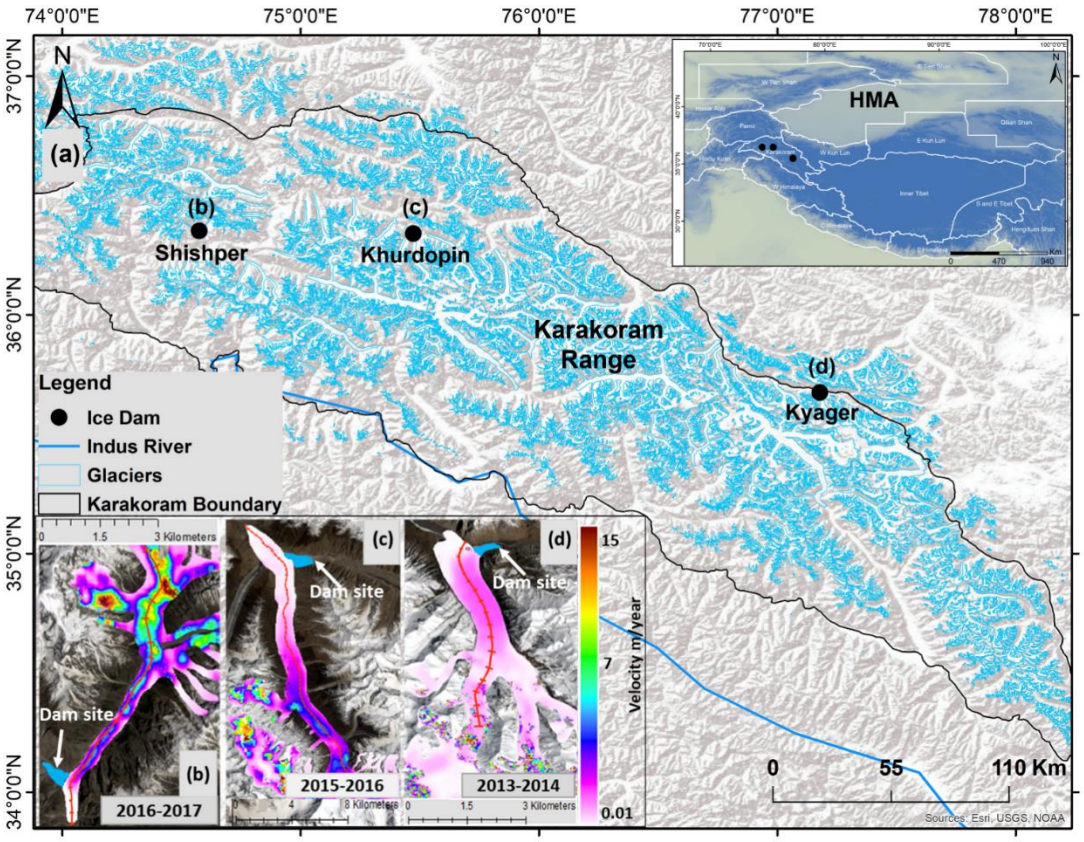

Figure 1: Overview of the study site in the Karakoram (a) and the High Mountain Asia (HMA) region; panels (b-d) present the extent of each glacier at a given time that surge speed has led to ice-dammed lake formation. The associated ice flow velocities are indicated. The background of panels (b-d) comprises, and the source is © Google Earth mages.

Figure 1 gives a good overview on the two lakes, but some things could be improved. Unless I missed a meaning of the color of the year lines, I would suggest using a fixed color scheme for the specific years, so that each year has the same color in each image. What is symbolized by the squiggly blue arrows?

Figure 1 in the original manuscript is now Fig. 2. We have modified the figure and the caption to address the referee's points.

Chapters 2.2 to 2.4 are very important as they explain the scientific basis of this article. However, all three chapters blur into another as it is not always easy to follow the structure of the article. For example, in 2.2, the eponymous “glacier mapping” is explained with the use of remote sensing and field observations and the lake volume calculation is introduced. Then, chapter 2.3 is called “field observation and lake volume measurement” – even if both have been mentioned before and even though the volume calculation especially is the focus of 2.4. A bit of restructuring and more suitable subtitles would improve the flow of reading.

The text within these two sub-chapters has been revised to make the sections distinct.

At the end of 2.3 (P8L189), you mention another way to compute lake volume – from DEMs. What method did you use here?

Lake volumes were calculated using the DEM of the empty lake basin from the mentioned DEM data or UAV data closest to the GLOF events, together with the lake extent and lake surface altitude obtained from high-resolution images. Field surveys of the Shishper glacier lakes were conducted in 2019, 2021, and 2022, and for Khurdopin in 2017 and 2018, using hand-held GPS and UAV (see section 3.2) to determine annual lake extents, lake depths, glacier heights and thickness, termini positions, and glacier surface displacements. The same process was applied to all ice-dammed lake outburst sites, and KH-9, ASTER, PALSAR-DEM, and SRTM were used for Kyager lakes.

It is difficult for me to understand the reasoning behind chapter 2.4. At the moment, it appears to be a mix between presenting the methodology and results, which does not improve the flow of reading. In the previous chapters you have explained the method of estimating/calculating volume (e.g. using field data, remote sensing, DEMs) – and now the authors present another chapter describing yet another method of estimating the lake volume using the lake basin approximation, even though they have previously stated that they have access to the lake basin once the lake is drained, by plumbing or with the help of DEMs. It would help the reader if the reason for this chapter was made clearer.

The 2.4 section has been updated to 3.4, and Text has been added to the beginning to explain the reasoning. Often, only remote sensing data are available, making it difficult to estimate the lake volume. This section introduces the approach of using simple geometric shapes to define lake volume.

As for the content of this subchapter:

Maybe I missed it, but Fig.2a contains the pentahedral lake shape, but only shows the comparison between DEM-based volume and tetrahedral volume in Fig2b. What is the reason for the pentahedral diagram?

The pentahedral assumption works better than the tetrahedral assumption. This issue is now explained in the revised text both in the methodology and result section.

Finally, what was the reason for assuming that the vertical cross-section of the lake at the dam is an equilateral triangle? Is this a common geometry for this kind of lakes? Also, if I understand correctly, this approach does not provide useful data because the estimated volumes are far too high (Fig2b). The authors state that lake depth is probably much lower, but do not present alternate estimations. Now of course it is completely acceptably to include an unsuccessful approach, but it should be (a) made clearer to the reader or (b) maybe moved to the Results or Supplements section.

The assumption of an equilateral triangle at the dam face is an inevitable outcome of the consideration as to whether the lake body is best described as an irregular tetrahedron. The alternative is a regular rectangle. In this section, we are developing a Method to explore whether this is the form of natural lake basins. The approach does provide a useful estimate in that the

misfit between the calculated volume and the observed volumes is systematic, allowing a potential correction to be applied to volumes calculated from remote sensing data alone. We have indicated at the end of this section that the implications of these calculations are considered within the Results section.

Figure 3 shows the very interesting correlation between surge periods and the occurrence of GLOF. It is a valuable contribution to this article. Unfortunately, it takes too much time to fully understand it. I would encourage the authors to spend more time on making this figure more precise and consistent, as this kind of figure is so important for the reader to fully grasp your work.

The figure has been updated accordingly to make it clearer and easier to read. In the revised text, it is now Figure 4.

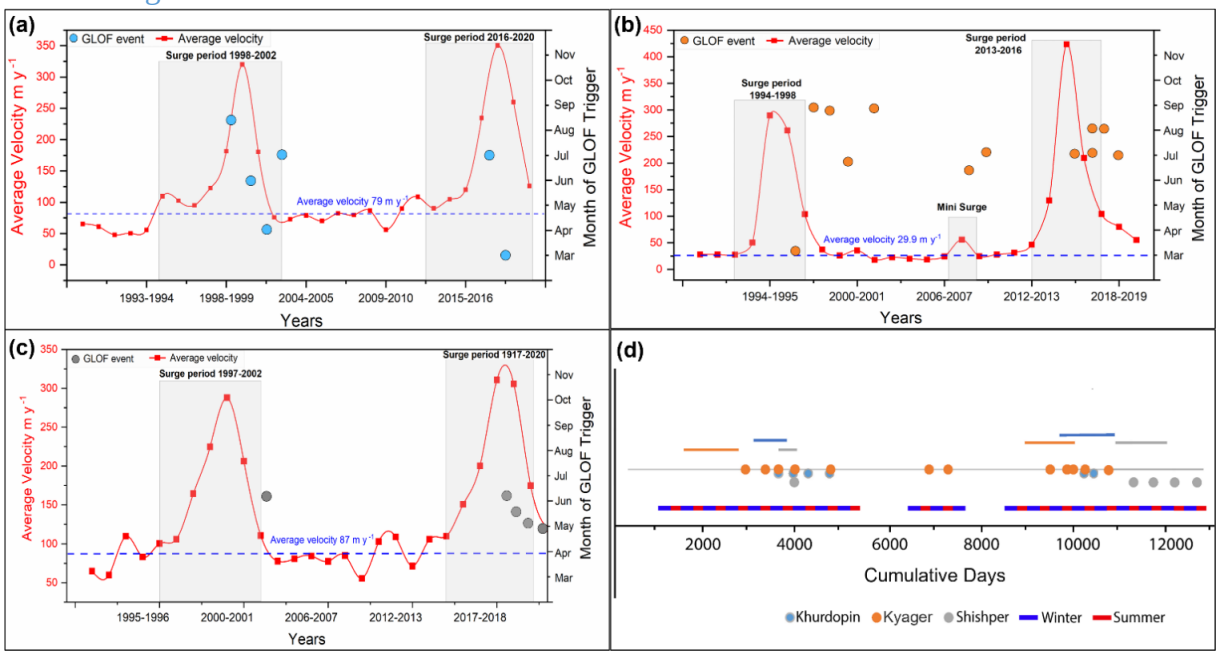

Figure 4: Relationship between glacier surges and GLOFs, with average annual glacier velocity during the surge and quiescent phases for three glaciers: (a) Khurdopin, (b) Kyager, and (c) Shishper. GLOFs for these glaciers occurred between the months of March to November. The combined analysis is presented in (d), illustrating the occurrences of GLOFs (dots) concerning periods of glacier surging (bars) as cumulative days since 1st January 1990. Some points are plotted below the timeline to avoid coincident positions. The blue and red lines show the winter (from October to April) and summer (May to September) seasons, with the GLOFs occurring dominantly in the summer months. Within panels a to c, the average surge velocity is given in red text, and the average velocity during the study period is given in blue text.

One example: the labeling of the x-axis is very strange in 3a-c, as the same interval sometimes means one year and sometimes three years. The vertical labeling is also difficult to read. A different type of labeling that, for example, only shows every five years (but written horizontally) and has constant axis ticks for the years between the labels would be much more appropriate and would clean up the picture a lot.

Modified and updated

Also, the font sizes are not consistent. Fig3b and Fig3c are missing a legend (comparable to Fig3a) which would explain the differently colored dots.

Modified and updated

And even after some consideration, I am not sure I understand Fig3d. The date seems to be 01/01/1990, but also some kind of timeline is indicated by the rising numbers below the bars. If this panel is only a combination of 3a-c, the authors should explain it more.

Modified and updated

In Fig. 4 and the preceding paragraph, the authors mention the exclusion of outliers from their data. In Fig.4, only two of the four excluded outliers are shown, but at least one of them appears to be relatively close to the main data spread. I would encourage the authors to include the reasoning behind the detection and treatment of the outliers – e.g., are they errors in the measurements, are they not representative etc.

Thank you for these observations, which we respond to below.

In general, Fig.4 is a valid support for the interesting investigation in the connection between surge velocity and lake size. However, it could be improved by a clearer legend and a more distinctive color mapping. At the moment, one color (light blue) is used for a trendline, glacier points, and the background shading (which should have a legend entry). Also, the triangles are explained two contradictory ways: In the caption, the authors describe the triangle lakes to have residual volume. In the legend, the triangles indicate drained lakes.

Thank you for these suggestions. The original Figure 4 is now Figure 5. These queries prompted us to reconsider the detection of outliers, so we sought the advice of a professional statistician. There are no statistical outliers, so we have redone the regression analysis and simplified the diagram. The interpretation of these results has not changed but should now be better expressed. The color scheme has been altered, along with caption and text modifications. The shading has been removed.

In Chapter 3 (P11-12 from L265-L290), the authors repeat the contents of chapter 2.4. They again mention the theory of the lake cross section resembling either an equilateral three-sided triangle or a square at the dam face. However, this approach was already described as unsuccessful in 2.4. due to the resulting volume estimations being much too high. As this section explains some methods more concise than before, these parts should be merged with its already existing counterparts in the Methodology, while the parts of the Methodology in 2.4 dealing with actual results should be moved here.

The Methods and Results chapters have been substantially revised to eliminate repetition and increase the clarity of the argument.

Figure 6 appears very full, but it conveys interesting results, especially in 6d. However, I would encourage the authors to spend some more time to "clean up" the figure. Some fonts are extremely small – maybe some information can be put into a separate table (like the L, E, and V data between c and d). I also wonder why there is no inset card for 6c.

Modified and updated

Technical corrections:

P1L1ff: The mountain range is called Karakoram, to distinguish it from the city of Karakorum, if I'm not mistaken. Please change it throughout the text.
Done

P2L40: Why is "Moraine Lake" capitalized?
Corrected

P3L92: "The current research focuses of Bazai and colleagues aims to leverage…" The plural of focus should be foci. à "The current research foci/priorities of Bazai and colleagues aim to leverage…"
Corrected

P3L98: A very nitpicky comment: In this sentence, the authors claim to have used "all available open and commercial satellite imagery sources", and they list a lot of sources, but surely not all. Please clarify if you indeed used the others, or rephrase the sentence.
Corrected

P4L124: Maybe a translation issue: The authors explain that lake extent and surface level can be used to "measure" the lake's volume. To my mind, "estimate" or "approximate" would be more accurate, because to really measure a lake's depth one would need to study its bathymetry.
Corrected to 'estimate'

P5L132: Probably will be fixed during editing, but "Gilgit-Baltistan Disaster Management Authority" has a smaller font size than the rest.
Corrected

P5L136: I would suggest swapping this paragraph with the next paragraph. With a little rewording, the reader would then first learn that all three glaciers are surging glaciers, and then learn about the method of measuring velocity. See also specific comment 1.
Modified and updated

P6L156: There is a colon in this line, the meaning of which I do not understand.
Text modified

P6L157: Maybe it's just me, but I still don't understand how you estimate the lake depth. If the lake is empty and you measure from the bottom to the shoreline, I understand the method. But

what role does the ice dam play in this calculation? It is explained better in Chapter 2.3, but here the explanation is somewhat fuzzy.
Thank you for these observations, which have been explained well in the revised manuscript.

P8L198: Before the reference (Dillencourt et al. 1992) there is a "to" too much.
Corrected

P9L232: "regional exemplars" à "regional examples"
Corrected

P10L246: "resultant" à "resulting"
Corrected

P10L248: "for ease of trend comparison" could be better rephrased as "to facilitate the understanding of the trends"
Modified as suggested

P10L251: The authors mention four excluded outliers, however, in Fig.4, there are only two outliers plotted. I would suggest adding the two remaining outliers.

Note that outlier detection has been modified to be more rigorous, and there are no outliers.

P13L291: In Fig.5, the x-axis label contradicts the caption. Are the values the volumes of tetrahedrons or pentahedrons? In any case, the axis label should indicate that the volume values have been divided by 10 to match the measurements.
Caption and figure modified

P13L297: "improving" à "improved"
Corrected

P16L357: The abbreviation GLOFs has already been explained in L45.
Corrected

P17L359: Am I correct in the assumption, that the values in 6c are divided by 10 to match the measurements? Because this time, it is not mentioned in the figure or the caption.

The figure and caption have been revised to ensure there is no error in the interpretation

P17L372: "Values of values n' < were associated…" à There appears to be a missing value (probably "0.60") after the "<". Also, the beginning of the sentence should be rephrased. In the same line, there is a space too much before the new sentence beginning with "Therefore, in..."
Corrected

P17L378-380: While the discussion in general does very well in summarizing the article, this part does not belong here. It introduces information better suited for the Methodology as it justifies the

reason behind this geometric approach. In the next paragraph, there are a few more sentences with the same problem.

We understand the point the referee is making here, but it is important to remind the reader of the relevant methodological assumptions within the discussion. This way, the reader is guided through the Discussion rather than having to go back to the Methodology for orientation. Nevertheless, we have edited the Discussion to ensure a consistent connection between the elements discussed.