Response File for

The 2024 cascading glacial lake outburst flood in the Thame Valley of Everest region, Nepal: process, impacts and implications

Response to RC2

This comprehensive study combines field data, climate/meteorological data, remote sensing data analysis and process chain modelling to describe the 2024 multi-lake outburst flood in Nepal Himalaya. The study is in general well-written and will be of interest for the audience of the NHESS journal.

Response: We would like to express our sincere gratitude to Dr. Adam Emmer for reviewing our manuscript and for his encouraging feedback. In the revised version, we have addressed all comments and provided further clarification on several concerns, which we believe has substantially improved the manuscript. The text in red font is our responses and in blue font is revision made in manuscript.

Several clarification requests / points for the consideration:

- Dangerous lakes identified in previous studies (Table 1) – What are the specific implications / recommendation derived from this event for revision of existing GLOF hazard assessment schemes that failed to identify this hazard?

Response: This event highlights two important limitations of existing GLOF hazard assessment schemes. First, many assessments apply minimum lake-size thresholds that exclude small glacial lakes from detailed evaluation. However, the Thame event demonstrates that relatively small lakes can still generate destructive outburst floods and should therefore be incorporated into hazard assessments. Second, current approaches often evaluate lakes individually and may overlook cascading processes. The Thame GLOF shows that failure of an upstream lake can trigger downstream lake breaches, substantially amplifying flood magnitude and impacts. Future GLOF hazard assessment frameworks should therefore (i) lower or reconsider lake-size thresholds used for screening potentially dangerous lakes and (ii) explicitly account for cascading and chain-reaction outburst scenarios between interconnected lakes.

Based on this response we have revised the Introduction section highlighting two key limitations of current studies and further elaborate on these implications and recommendations for future GLOF hazard assessment frameworks in the Discussion section 5.4.

In introduction: This highlights limitations of existing GLOF hazard assessments (Table 1), particularly the use of minimum lake-size thresholds for screening glacial lakes and the limited consideration of cascading outburst processes, whereby failure of an upstream lake can trigger downstream lake breaches.

In discussion (Section 5.4): The Thame event suggests that existing GLOF hazard assessment schemes should be revised in two key ways: (1) lake-size thresholds used to screen potentially dangerous lakes should be lowered to include small lakes capable of producing damaging outbursts, and (2) assessments should explicitly evaluate cascading processes, whereby failure of an upstream lake can trigger downstream lake outbursts and amplify flood impacts.

- Lake volume estimate – what is the reason for using empirical equations in the study if high resolution 1-m post-GLOF DEM was generated, allowing for precise release volume estimate? The discussion of the well-known uncertainty associated with empirical equations can be then removed from section 5.3

Response: Thank you for your comment. Now, we have revised the text by updating the drained volume using post-GLOF drone-derived DEM (1 m). We have made necessary changes in the data/method section as well as in the results. We compared the drained volume obtained through empirical estimation and the reconstructed through post-GLOF DEM. The drained volume of upper lake from empirical estimation was underestimated by 64%, thus, we re-runed the model to obtain updated results. In the revised version, we updated the modeling results and figures by replacing the input hydrograph (Fig. S3) and drained volume from drone-derived DEM, keeping other factors constant. Since, the drained volume of upper lake was increased from drone-derived DEM estimates, the resultant peak discharge, arrival time and velocities were increased simultaneously. Notably, more or less, accuracy assessment was similar. We have updated the results throughout the manuscript. Additionally, following the suggestions, we have also removed the well-known uncertainty associated with empirical equations (Section 5.3) and discussed briefly the comparison of both methods (empirical estimates and DEM derived estimates).

In methods (Section 3.2): A high-resolution (1 m) DEM was acquired via uncrewed aerial vehicle (UAV) surveys on 24 May 2026. The drainage volume of the upper and lower lakes was reconstructed using the lake outlines and the drone-derived DEM. The post-GLOF lake water surface elevation was estimated by sampling elevations along the lake perimeter from the DEM and assigning the median elevation to all cells within the post-GLOF lake outline, thereby creating a flat-water surface. The pre-GLOF lake surface was reconstructed using the same approach. The reconstructed pre- and post-GLOF water surfaces were differenced, and the resulting elevation differences were multiplied by the grid-cell area and summed to estimate the drained lake volume. For this, lake outline delineated before (2024-08-15) and after (2024-08-18) the event was utilized. The water volumes of upper and lower lakes were empirically estimated using average of nine area-volume relationships (see Tables 3 and S1). Further, the obtained drained volumes from drone-derived DEM were also compared with empirically estimated drained volume (refer Text S1 and Table S1).

In results (Section 4.2): A total of approximately 7.7 ×105 m^3 of water was released from both lakes during the event. The drone-derived DEM and empirical methods yielded broadly comparable estimates of total drained volume, differing by 28.3% (Text S1). The lower lake estimates were in close agreement (2.9% difference), whereas the upper lake showed a larger discrepancy (64%).

In discussion (Section 5.3): Comparison of the empirical and drone DEM-derived estimates (Text S1) shows good agreement for the lower lake, with only a 2.9% difference in drained volume. In contrast, the empirical approach underestimated the upper lake drained volume by 64%, resulting in a 28.3% underestimation of the total drained volume (Text S1). This highlights the advantage of post-GLOF DEM-based reconstruction for estimating drained volume, particularly where lake basin morphology is complex. However, post-GLOF DEM-based drained volume reconstruction is also sensitive to lake outlines.

- Modelling – what are the implications of modelling the event for process understanding? What are the implications for model development? please provide the justification of friction angles used (Table 4)

Response: We thank the reviewer for this valuable comment. We have expanded the discussion in the revised manuscript (Section5.3) to better highlight the implications of the modelling results and to justify the parameters used in Table 4.

The r.avaflow simulations were conducted to reconstruct the event and evaluate the plausibility of the proposed outburst scenarios. The modelling improved process understanding by quantifying flood propagation, travel times, inundation extent, and the role of cascading lake interactions, demonstrating how relatively small headwater lakes can generate significant downstream impacts.

In discussion (Section 5.3): The modelling demonstrates that small, previously overlooked glacial lakes can generate hazardous cascading outburst sequences when hydraulically connected. The simulations indicate that downstream impacts were controlled not only by the initial outburst volume but also by progressive lake interactions and sediment entrainment. These findings highlight the importance of considering multi-lake systems in future GLOF hazard assessments.

From a model-development perspective, this event highlights both the capability of r.avaflow to simulate complex cascading GLOF processes and the challenges associated with estimating drained lake volumes, and sediment availability and mobilisation. These findings emphasize the need for improved parameter constraints and high spatial resolution DEM for future applications.

In methods (Section 3.4): The parameters presented in Table 4, including the internal friction angle (25°), basal friction angle (15°), and fluid friction number (0.05), were primarily adopted from previous r.avaflow applications for GLOF and debris-flow modelling (Mergili et al., 2020b; Rinzin et al., 2025; Zhang et al., 2025; Chen et al., 2026) and subsequently refined through parameter optimization during the initial stages of the simulations. The selected parameter set yielded good agreement with the observed flood extent and flow routing, resulting in satisfactory accuracy assessment scores. We have revised the text accordingly.

- Climate and meteo triggering / pre-conditions – Fig. 6 shows peak temperatures 2 weeks before the GLOF and peak precipitation week before the GLOF; how this underpin / undermine increased lake water level triggering hypothesis?

Response: We thank the reviewer for this important comment. To better assess potential hydro-meteorological preconditioning, we analyzed temperature and precipitation anomalies during the month preceding the GLOF. The results show that both temperature and precipitation frequently exceeded the 90th and 95th percentile thresholds, with particularly high temperatures approximately two weeks before the event and elevated precipitation during the week preceding the GLOF. These conditions likely enhanced glacier and snow melt as well as catchment runoff, contributing to increased inflow to the lake system and potentially elevated lake water levels prior to the outburst. While direct observations of lake-level changes are unavailable and therefore a causal relationship cannot be conclusively established (we also checked SWOT data), the observed meteorological anomalies support the hypothesis that hydro-meteorological conditions may have preconditioned the lake system and increased its susceptibility to failure. We have added a sentence in discussion to clarify this point in the revised manuscript. Further, for triggering analysis and uncertainties, we would like to request to see the response to Reviewer 1.

Section 5.2: Consecutive days of extreme precipitation and anomalously high temperatures prior to the event (Fig. 6) may have contributed to hydro-meteorological preconditioning prior of the lake system. Although direct observations of lake-level changes are unavailable and a causal relationship cannot be conclusively established (Fig. S11), the observed meteorological anomalies support the hypothesis that these conditions increased the lake's susceptibility to failure.

- The 90th and 95th percentile in climate analysis and Fig. 6 – is it referring to August values or year-round values? It would be interesting to see whether August 2024 was anyhow exceptional compared to Augusts in previous years

Response: We thank the reviewer for this comment. Figure 6 presents daily mean temperature and precipitation from 15 July to 1 September 2024. The lines indicate the 90th and 95th percentile thresholds derived from the long-term daily climatology (1990–2024) and red color (on bar and symbol) indicates days on which temperature or precipitation exceeded those thresholds.

To place the event in a longer-term climatological context, we additionally compared the 30-day period preceding the GLOF event (17 July–15 August) in 2024 with the same period during 1990–2024. The analysis shows that the mean temperature during the pre-event period in 2024 was the highest in the entire record, exceeding both the 90th and 95th percentile thresholds (Figure S6a).

These results indicate that the month immediately preceding the GLOF was exceptionally warm and wet compared with previous years, supporting the interpretation that hydro-meteorological conditions may have enhanced meltwater production and runoff, thereby preconditioning the lake system prior to the outburst. We have added this analysis and discussion to the revised manuscript.

- Section 3.2 – please provide more methodological details on the engagement with stakeholders and local residents; what were the insights about the timing (duration?) of the flood (actually not found in results section)?

Response: We thank the reviewer for this suggestion. During field visit, we engaged with local residents of Thame Village, stakeholders and rural municipality to gather insights on the timing and impacts of this event through interview and informal discussions. These consultations provided qualitative information on the timing and progression of the flood, observed impacts, and community experiences before, during and immediately after the GLOF. We have revised the text (methods and results) accordingly.

Interviews with local residents indicated that the days preceding the GLOF were perceived as unusually warm. Although the reported timings varied among respondents, residents consistently stated that the flood occurred during the afternoon of 16 August 2024. Records from local authorities and other stakeholders indicate that the flood reached Thame Village at approximately 13:30 local time. A Planet satellite image acquired at around 10:00 local time on the same day showed no evidence of an outburst at the source area (Figure 5). Together with the reconstructed flood travel time of approximately 20-25 minutes from the source lakes to Thame Village (Section 4.4), these observations suggest that the GLOF was initiated at around 13:00 local time.

- Section 3.5 – overall too brief; please provide more details on this cross-verification with GaoFen and gathering of impacts in the field?

Response: Reported damage to trekking trails in the Thame Valley was cross-verified using high-resolution GaoFen-2/7 satellite imagery by comparing the reported length of damaged trails with the length of visible post-event damage observed in the imagery. We have revised it.

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- 5.1 while there is obvious causality between climate change, glacier retreat and proglacial lake expansion, the attribution is not really addressed in this section; are there any implications of this case study for ongoing efforts of attributing GLOFs to climate change?

Response: We thank the reviewer for this observation. Our intention was not to conduct a formal climate attribution analysis but rather to discuss the linkage between climatic warming, glacier retreat, and the formation and expansion of the source lakes. To avoid confusion, we have revised the section title accordingly.

5.1 Evolution of glacial lake in response to climate change induced glacier retreat

- 5.4 Future GLOF hazard – please comment on potential magnitude of future GLOFs (smaller vs. larger than the 2024 event?); table S4: please check carefully (bedrock banks instead of lateral moraines made of bedrock; seismicity has no influence on bedrock dam (unless it triggers slope movements); what GIS modelling has been used for topographic potential to rock avalanches?)

Response: We thank the reviewer for these valuable comments. Regarding future GLOF hazard, we have expanded Section 5.4 to discuss the likely magnitude of future events. Although a renewed outburst remains possible if a GLOF were to originate from the upper lake, the substantial reduction in the lower lake volume following the 2024 event suggests that the magnitude of future cascading floods is likely to be lower than that of the 2024 event in the near term. We also note that continued glacier retreat and future lake evolution may alter the hazard potential over longer timescales.

We have revised the Table S4 according to the suggestion provided. We agree that Seismicity has no influence on bed rock unless it triggers slope movements. We have added this information in the table. The reference to seismicity was included only to highlight that the study area lies within a region of high seismic activity. To assess the potential for rock avalanches, we performed a simple GIS-based topographic runout assessment following Dubey et al. (2023), considering slopes steeper than 30° as potential source areas and evaluating their potential to reach the lakes. We have revised accordingly.

Although a renewed outburst remains possible if a GLOF were to originate from the upper lake, the reduced lower lake volume suggests that the magnitude of future cascading floods is likely to be lower than that of the 2024 event in the near term. Continued glacier retreat and future lake evolution may, however, alter the hazard potential over longer timescales. Therefore, regular monitoring of upper glacial lake is recommended using remote sensing technologies and field assessments.

- 5.5 DRM – as for the consideration of small lakes – please consider refering to this work: https://www.nature.com/articles/s43247-025-02758-4; as for the GLOF hazard and risk mitigation frameworks, this may be relevant reference: https://www.sciencedirect.com/science/article/pii/S2095927325011521

Response: Following the suggestions, we have cited these references.

- while hazard is a centerpoint of the study, it would be good to analyze or discuss whether / how change of the exposure component modified resulting GLOF risk (see also: https://www.nature.com/articles/s44221-024-00254-1)

Response: We agree with the reviewer that any changes in exposure will modify overall GLOF risk. We did not particularly analyze the changes in exposure as it was not objective and manuscript would be too long. *We have cited the suggested article*.

S2: how a distinction between floating and grounded iceberg was done (and isn't part of the definition of an iceberg that it is always floating)?

Response: We distinguished drifting and grounded icebergs by comparing their positions in sequential satellite images within a GIS environment. Drifting icebergs exhibited measurable displacement between image acquisitions, whereas grounded icebergs remained stationary since they were in contact with the lake bed. We added this information in supplementary figure caption.

S3: please give a location of this area detailed in the image

Response: We assume this comment is for S8 and have revised accordingly providing a location.

S9: please add a scale for embedded images

Repones: The figure has been revised adding scale to all embedded images

To sum up, I recommend some moderate revisions (especially in the discussion section).

Response: We again thank you for your time and efforts to review the manuscript and provide valuable comments and suggestions, which has been addressed and revised accordingly that has helped to improve the manuscript significantly.

References.

Dubey, S., Sattar, A., Goyal, M. K., Allen, S., Frey, H., Haritashya, U. K., and Huggel, C.: Mass Movement Hazard and Exposure in the Himalaya, 11, e2022EF003253, https://doi.org/10.1029/2022EF003253, 2023.