

Reviewer#1

The study by Rinzin et al. analyses the downstream exposure and vulnerability of infrastructure, buildings and people to glacial lake outburst floods in Bhutan. Their analysis relies on a dataset >200 glacial lakes, a globally available digital elevation model and OSM data. Using HEC-RAS, the authors simulate a scenario for each lake and compare flooding extents, depths and velocity to the locations of the elements at risk.

In general, this is a well-conceived study that leverages hydrodynamic modelling to address some of the weaknesses of previous studies that made quite simplifying assumptions about flood wave propagation and the extent of their impact. However, there are still a few issues with the study which I will outline below. All in all, I recommend major revisions before the manuscript should be published in NHESS.

Many thanks for providing valuable feedback and a positive review of our manuscript. The comments were highly valuable, which helped us improve the quality of our manuscript. We are pleased to provide our response in the following, where our responses are highlighted in blue fonts for better visibility

Major comments:

The parameter choice relies on previously published data (flood volume). However, the choice of parameters does not consider the variability of this data, but rather takes point estimates. For example, the choice of using the median of reported percentages of drainage volume is considered the "most likely flood volume" (L 212). However, if you have a bimodal distribution of partial drainage volumes, then the median is not the most likely flood volume. Thus, it may be useful to not pick out the median scenario, but one that is at the upper end of the distribution, thus giving more weight to extreme scenarios. Same is true for the volume-area relation that may only represents an average of the breadth of possible scenarios. Schwanghart et al. (2016) showed that results of GLOF modelling are not sensitive to uncertainties in the V-A relation for large lakes, but that these uncertainties matter for smaller lakes. I acknowledge that the study already comprises many simulations with quite a heavy computational load. However, it should be at least discussed that the current approach lacks a consideration of the large variability of possible outburst scenarios and that average scenarios may not capture the worst-case scenarios.

We thank the reviewer for raising this important concern. We recognise that this is just one set of scenarios, but we cannot run them all due to time and computing constraints. We therefore pick the median scenario, so they are directly comparable, to provide an estimate of the overall, relative danger and to give a moderate scenario, so we are not essentially modelling outliers. We are now not using the term 'most likely scenario' but a more specific, 'medium scenario' in all appearances in the revised manuscript. We have also addressed this limitation and its implications in the discussion section in the revised manuscript (lines 716 to 724).

"Our drainage volume and peak flow calculations are based on empirical equations and the previous GLOF events, with scarcely documented detailed characteristics (Shrestha et al., 2023). Employing such proxy parameters is reasonable for this study as our aim is to provide an overview of GLOF risk in Bhutan based on the downstream impact. The modelled GLOF

scenarios for each lake are directly comparable, enabling an assessment of the overall and relative levels of danger, and representing a moderate scenario. We recognize however, that this is just one set of scenarios. Due to time and computational constraints, it was not feasible to simulate all potential variations. Future studies focusing on the detailed impact of specific glacial lakes or on specific downstream communities must be grounded on site-specific scenarios informed by situational triggering factors and dam composition and geometry. The study should also consider the site-specific worst-case scenario, considering the future climatic conditions.”

A simulation of one or few past GLOFs and comparison of actual with simulated peak discharges would help gaining confidence into the model and its ability to realistically model GLOF dynamics. How can readers evaluate how well your model actually works? This would also enable to tune parameters and eventually study how sensitive the results are to uncertainties in the parameter values.

While evaluating model performance and parameter tuning based on the past event is necessary, it was not feasible due to the absence of previous GLOF events with observed characteristics in the region.

Based on our experience, we believe that reconstructed values from past events may not accurately represent future GLOFs, as each event is unique due to distinct geomorphological conditions and event-specific characteristics (Rinzin et al., 2025). Nevertheless, we are confident in the performance of the HEC-RAS model for simulating GLOF inundation, as evidenced by its successful application in a wide range of previous studies throughout the region (Maurer et al., 2020; Sattar et al., 2021; Rinzin et al., 2023; Sattar et al., 2022).

However, acknowledging the reviewer’s concern, we will add sensitivity analysis considering the variability of Manning’s n (between 0.040 and 0.070, the value range suggested by another reviewer) and lake size variation between 0.01 and 4.5 km². For lake size, we considered four scenarios: >0.05 km², 0.05 to >0.1 km², 0.1 to 1 km², and >1 km² in line with the size category we considered for calculating drainage volume. This sensitivity analysis will be conducted within the same basin to uniformly assess downstream impacts. Results of the sensitivity analysis will be added, and their implications will be discussed in the revised manuscript.

There are numerous instances where ambiguous or imprecise terms are used. Generally, I think that the terms threat and danger(ous) should be avoided, and that rather terms like hazard (probability of a potentially adverse event happening), exposure (how much are people or infrastructure within reach of a hazardous event), vulnerability (how susceptible are the exposed people or elements) and risk (the combination of the previous, quantitative metrics) should be used as they have a precise and measurable meaning. Threat and danger in turn have a qualitative and subjective meaning. Your work mainly aims to address the exposure of various elements at risk, and you quantify and aggregate the exposure so that it becomes an attribute of each lake. So, to this end, you quantify a lake-specific exposure index.

The same concern has also been raised by other reviewers. We have changed the terminologies consistently to the hazard, vulnerability, exposure and risk in all appearances in the revised manuscript.

Minor comments:

41: You state the number of 6907 fatalities, and backpedal later that this number is 80% attributed to a compound event involving the Chorabari outburst. The number of fatalities that can be clearly attributed to the Kedarnath event is probably very uncertain and much lower than those 80%. I would try to tone this more carefully, avoiding reporting numbers with high precision, that actually have a high uncertainty.

We have now amended this as:

“However, this reported number is highly uncertain, firstly due to scarce documentation of the past events, while 80% these reported deaths in HMA are associated with a single compounding event involving Chorabari glacial lake and widespread cloud outburst-induced debris flow within the basin in 2013”

49: Provide a definition of danger, in particular if your aim is to quantify it. Rather, as pointed out above, avoid this term entirely.

We replaced this ‘danger’ with ‘risk’

81: This should be 31%, not 0.31%.

Thanks. Amended.

280: How was the HEC-RAS interfaced with? It would be great if you could add a technical description in a paragraph that details how you interfaced with HEC-RAS. I assume that you used the HEC-RAS controller to automate the tasks.

We did not use the HEC-RAS controller as we had to define separate upstream boundary conditions for each lake, which we believe is not straightforward, even using the HEC-RAS controller. Therefore, all models were set up manually, and simulations were done manually using computers in the geospatial laboratory at Newcastle University.

318f: Is it common to take the product of depth and velocity as damage level? Is it useful that the damage level of a water depth of 1 m and velocity of 5 m/s is the same for a water depth of 5 m and a velocity of 1 m/s?

It is not common, but it is a robust approach to account for both depth and velocity to calculate the damage level, especially in mountainous terrain conditions, since flow velocity plays a critical role in causing damage to infrastructure. Regarding the discrepancy where the impact of a water depth of 1 m and a velocity of 5 m/s is considered the same as that of a water depth of 5 m and a velocity of 1 m/s, we can say that the damage level might also depend on how long the structure remains submerged in water or kinetic energy associated with the debris content in the flow. However, for this first-order risk assessment, we believe it is reasonable to assume the damage level is the same, since we do not account for other details such as the content and actual value of the building.

540: It would be helpful to use a stringent and precise terminology here. What is devastating in comparison to damaging? Was the Missoula flood devastating, but not damaging, because no humans were affected (not sure whether this is true)? In simple terms, the risk of GLOFs is mainly determined by the exposed elements at risk, not by their hazard?

594f: I don't think that your approach challenges traditional susceptibility analyses. Rather, your approach may complement them. In contrast to susceptibility studies, your analysis assumes that the outburst probability is homogeneous, thus neglecting any variations in dam stability and lake exposure to avalanches and landslides.

Thanks for this suggestion. We have now corrected this statement as follows:

“Our study complements the conventional dangerous glacial lake assessments approach by redefining which glacial lakes pose the greatest danger to the downstream settlements”

719-721: Considering a risk framework, this is a somewhat trivial statement.

This is now corrected as follows:

However, the destruction and damage caused during the GLOF events are not only due to the hazard but also depend on their interaction with downstream exposed elements.

729: Please avoid the high precision of numbers when their estimates are prone to large uncertainties.

Thanks. It is now corrected as:

The analysis revealed that over 20,000 people, 2600 buildings, as well as other infrastructure such as roads and bridges and farmland are exposed to GLOF in Bhutan

Table S1: As the table spans several pages, it would be great to have the header row of this table on each page.

Thanks, amended as suggested.

Table S2: Be consistent in the number of digits that you report. Up to 8 digits behind the decimal point suggest an accuracy that you probably don't have in your measurements. When reporting counts (Bridges), use integers.

Thanks, the table is amended as suggested in the revised manuscript.