

Response to Reviewer 2 comments

Westoby *et al.* 'Numerical modelling of Glacial Lake Outburst Floods using physically based dam-breach models'

Anonymous Referee #2 comments:

This paper discusses a detailed modelling approach to assessing dam breaches associated with Glacial Lake Outburst Floods. I think it could be published following some moderate revisions and further clarification.

Specific comments:

The paper is not always clearly written for the general reader and much of the discussion of the results section should be rewritten for clarification.

We will review the manuscript with general readers in mind and will endeavour to make our explanation and discussion of key results and points as possible.

I would also ask that the paper better identify and discuss the problem of uncertainty. What does this uncertainty affect? Where does it come from and are there intractable issues? There is much literature on uncertainty analysis in the use of climate change models for instance and reference to some of this literature should be made because many of the problems that are faced by the earth science researchers are not dissimilar to those faced by climate modellers (e.g. initial condition uncertainty; the problems associated with ensemble modelling, model uncertainty and model variability, the uses and abuses of Bayesian modelling and distinctions between frequentist approaches).

The reviewer makes a very good point here, and we agree that the manuscript perhaps does not adequately consider the significance of uncertainty (and equifinality) in the context of glacial lake outburst hazard assessment. To address this, we will first expand sub-section 3.1, with a focus on the scope and numerous sources of this uncertainty and its potential significance for the problem at hand. The discussion section will be expanded to re-visit this point in light of our results. Yes, there are a number of intractable issues here, such as the logistical impracticalities with quantifying moraine grain size distributions and other mechanical and (hydro)morphological characteristics of the sediment in situ (such as the roughness coefficient), which has implications for defining the initial parameter ranges and comparing behavioural ranges with those observed in the field. We will make a point of specifically highlighting these issues in the revised manuscript. We also note the reviewer's suggestion to consider relevant climate modelling literature, and will additionally include a discussion of the wider significance of uncertainty in geoscience modelling.

In the case of the use of Bayesian statistics (page 490), the paper needs to discuss how the prior was identified and this is not done sufficiently. I am also not sure that the use of the idea of equifinality is sufficiently described and rationalized. What does the concept add and it is being used properly? The implications of equifinality and convergence are profound for prediction, retrodiction and induction and these need better assessment.

In this context, the likelihood score for the each parameter ensemble after conditioning on the first likelihood function (final breach depth) is taken to represent the prior likelihood. We agree with the reviewer that this is not necessarily clear, and will further clarify our method in the revised manuscript. The latter part of this comment echoes similar points raised by Reviewer 1, and we will clarify our reasons for wanting to quantify equifinality in the dam-breach modelling, and the wider significance of equifinality for outburst flood modelling, earlier in the manuscript so that it becomes immediately clear why we focus on it.

I could not see why HR BREACH model was used, nor whether it is better than other types of models. I am not a modeller so I would need a better assessment and justification of this model over other ones.

The main reason for using HR BREACH is its improved physical basis when compared with other commonly used models for simulating dam-breaches. We emphasise this point on page 485, line 7 onwards. An additional feature of the model is its in-built capability to handle stochastic (Monte Carlo) parameter space sampling, which makes it ideally suited for our probabilistic modelling approach. We will expand this paragraph to expand on, or state these points.

Also is the 2D approximation appropriate for a 3D modelling issue such as dam breaches? It may be but this needs to be discussed in more detail.

We assume that the reviewer is referring to the use of ISIS 2D with this comment. Yes, the 2D approximation is highly appropriate, specifically because of its ability to simulate multi-directional and multi-channel flows (in contrast, 1D models are only capable of routing flow in a downstream direction), thereby representing a significant improvement over one-dimensional codes; the use of which has typically been the norm in the glacial outburst flood literature.

Dam breach outburst floods are often highly chaotic, and exhibit flow phenomena including super-elevation of flow around channel bends, hydraulic jumps (transitions between supercritical and subcritical flow regimes) and the formation of flow recirculation zones. A 1D model is incapable of simulating any of this behaviour, whereas fully 3D models are currently incredibly computationally demanding. In contrast, the multiple model runs required in this study could be achieved in ISIS 2D within a practical time-frame. As suggested, we will expand our reasoning behind our choice of hydrodynamic model in sub-section 4.5.1.

How representative is the site used for this study? In other words, how applicable to other situations is this approach? This is not adequately demonstrated, but if it was applicable and showed that the approach produced valuable information then this paper would be of value.

Dig Tsho exhibits many of the key (geo)morphological characteristics of extant and breached moraine-dams in regions including the Himalaya, the Andes, Alps and North American Cordillera. Additionally, its failure was triggered by an overtopping wave as a result of ice avalanching into the glacial lake – this is the most widely documented trigger mechanism for moraine dam failure in the Himalaya and Andes in the published literature (see, e.g. Richardson and Reynolds, 2000) and is therefore highly representative of other moraine dammed lake systems. We will include a discussion of the key similarities between Dig Tsho and other moraine-dammed lakes in our description of the field site (section 2), and its appropriateness for use in this study.

At present you have shown that moraine material roughness and sediment characteristics play a major role in dam breach development. So, how can we use this model more widely in regions where assessing sediment character of moraines is prohibited or difficult? This question needs answering or more discussion.

We touch on this point on page 505, line 22 onwards in the manuscript. Issues of site-specificity come into play here, and we will update sub-section 6.2 to consider this in far more detail. As the reviewer points out, the key here is the sedimentological character of the moraine. Our results suggest that quantifying moraine material roughness is key. The inaccessibility of many moraine dams often makes field investigation logistically difficult or impossible. One solution could be to survey a selection of moraines in a region, and, assuming that moraine geology and mode of moraine deposition is similar between adjacent glacier-moraine systems, produce a database of regionally specific 'type' moraine sedimentologies that could be taken as representative of all moraines in the region, including those that have not been investigated in detail, but which may need to be assessed for their outburst flood risk. This may then go some way into adapting our reconstructive approach for

predictive GLOF modelling, but would require comparison with other moraine-dammed failure for validation.

The increasing availability of fine-resolution digital terrain models is likely to overcome problems associated with quantifying moraine geometry (e.g. length, depth, width) in the level of detail required for advanced dam-breach modelling (i.e. down to the metre-scale), with the remaining unknown being the bathymetry/hypsometry of the lake. Commonly used methods to address the latter include the use of empirical models that relate lake surface area to depth, however, these are accompanied with many of the same problems that accompany the use of empirically derived equations for calculating breach peak discharges or time to peak, in that they may have been derived from case studies that might not be truly representative of the moraine-dammed lake under investigation. We will significantly expand our discussion of the problems that remain as the reviewer suggests, as this will also be of value for highlighting potential avenues for future research in this field.

Supporting references

Richardson S and Reynolds JM (2000) An overview of glacial hazards in the Himalayas. *Quaternary International* 65, 31-47.