Reply to Referee Comment #2 by an Anonymous Referee

General Comments

General Comment #1:

As I can see, a fair bit of work has been carried out, however, the current form of the manuscript lacks sufficient novelty and several vital information. Moreover, the usage of a few terminologies such as 'outburst', and 'risk' need justification. Details on the numerical aspects of the flood model set-up, which is vital in justifying the impact assessment are also missing in the text.

We thank the referee for their evaluation and refer them to our replies to General Comments #5, #8, and #10.

General Comment #2:

1. Introduction- In the current form, the introduction projects more or less about the study region, and flood incidences. It is understandable that the focus of the study is on a mountainous region, however, following a generic (or top-down) approach to flood risk, and other flood-related issues may be desirable. A few statistics on concomitant climate change impacts may also be added here to show the severity of the flooding events.

We agree with the referee that a more generic introduction to flood risk in a globally changing climate might be interesting and are thankful for this suggestion. However, as we submitted our manuscript to the special issue "Estimating and predicting natural hazards and vulnerabilities in the Himalayan region" we prefer to keep our introduction focussed on this region in general and the Pokhara valley as our study area in particular. We added information on projected climate change impacts on the Hindu-Kush Himalayas starting from LL31: "Current projections of cryospheric change in this mountain belt include a continued total glacier-mass wastage of up to 64 ± 5% by the end of the century under the RCP8.5 scenario (Kraaijenbrink et al., 2017) as well as permafrost degradation (Bolch et al., 2019). These changes will likely result in a destabilisation of mountain slopes and increase in meltwater volumes stored in lakes impounded behind potentially instable natural dams (Hock et al., 2019). Thus, the potential for hazards caused from these instabilities, including sudden floods, is likely to increase in the future. The Pokhara valley in Nepal, home to the nation's second largest city, is a prime example of such a Himalayan valley with rapid socio-economic development: […]."

General Comment #3:

3. Section 3.2- Not enough justification is provided on the selection of the ten peak discharge scenarios as inputs to the HEC-RAS model. Moreover, why did the authors consider a range between 1,000 and 10,000 m3/s? Please elaborate.

We ask the referee to refer to our reply to Referee #1's General Comment #2 regarding our justification of the tested range of peak discharge scenarios.

General Comment #4:

> 4. In continuation to the previous query, a major discrepancy arises with the class intervals (1000 m3/sec) between each peak discharge. What if there is a peak-discharge falling in the mid-way of two end values, which may not be incorporated appropriately within the flood model, but will add up the impacts on the communities.

We are unsure what the referee means by "major discrepancy". The scenarios that we present here collapse a number of assumptions into a few scenarios. By definition, none of these (or any other scenario) can account for all possible outcomes. Instead, the scenarios offer some general and consistently structured insight into the extent of flooding given for a range of peak discharges. We are interested here in a first-order appraisal of how inundated area scales with peak discharge instead of providing detailed flood-prediction maps for every possible flood size.

General Comment #5:

> 8. Details of the time step of the HEC-RAS model simulation, final resolution of flood inundation maps, and courant number must also be added in section 3.2. Further, the justification of considering ALOS DEM (which is a freely available global product) as the bathymetry map for the study area may also be added, as sensitivity (if any) from the DEM will be reflected as inaccuracies in the set of flood inundation maps.

We added information on the resolution of inundation maps and the used ALOS DEM.

The 5-m ALOS 3D enhanced DEM is a commercial product and has the highest available resolution for our study area. Yet especially the narrow gorges of the study area are not well resolved such that we manually corrected cross-sections with field data (see our reply to Referee #1's Specific Comment #3). We agree with the referee's statement that DEM resolution is a constraint on the accuracies of the flood inundation maps, but had explicitly acknowledged this in the original manuscript version: "The accuracy of our results hinges on the accuracy of river cross-sections and the estimates of channel and overbank roughness (Manning's *n*; Westoby et al., 2014; Wohl, 1998). Previous studies of HEC-RAS for outburst floods have used mostly coarser digital elevation data than the 5-m ALOS DEM we used here (Mergili et al., 2011; Somos-Valenzuela et al., 2014; Wang et al., 2018; Zhang and Liu, 2015). The stereo satellite imagery forming the basis for this DEM was acquired between 2006 and 2011 and excludes channel changes by the May 2012 flood (Gurung et al., 2021). We minimised potential resulting effects on our models by manually adjusting cross-sections with our additional field-surveyed elevation data." (LL277-282).

Further, we model one-dimensional steady state flow and, thus do not specify time steps or a Courant number in our HEC-RAS models. The necessary model inputs for this approach (Manning's *n*, upper and lower boundary conditions, baseflow in the tributaries) were accounted for in our original manuscript in LL129-136. Please also refer to our reply to Referee #1's Specific Comment #2 for our reason for avoiding unsteady-state modelling.

General Comment #6:

> 10. The description of "Hazard" in the manuscript is ambiguous. Hazard indicates the severity of an event and is usually represented in terms of floodwater depth, velocity, the residence time of floodwater, etc. As a result of which, directly attaching the discharge scenarios to different levels of hazards is a very preliminary attempt. In another way, authors might consider terming them as low to high hazard classes rather than providing hazard classes as such.

Although our models yield information on floodwater depth and velocity (LL181, 186, 188 and Fig. 5, Fig. 6), we refrained from using these as metrics of inundation hazard due to the large number of tested scenarios. Classifying flood hazard based on, for example, inundation depths for ten different peak discharge scenarios each is arguably more detailed, but also much harder to communicate. The main aim of our paper was to raise awareness that large, rarer non-meteorological floods, which are so far hardly considered in hazard assessments, may affect several rapidly expanding settlements and infrastructure. Thus, we deliberately opted for a simple approach and classified hazard based on whether a given area or object would lie within the inundation limits of a given flood magnitude on the basis that higher flood peak discharges are exceeded more infrequently. Hence, objects and areas within the inundation limits of smaller peak discharge scenarios are more likely to be affected and are, thus, attributed to a higher-hazard class.

General Comment #7:

> 12. How did the authors carry out calibration and validation of the flood inundation outputs? Without this, the impact assessment over various land-use classes does not seem fitting.

Please also refer to our reply to Specific Comment #4 and Referee #1's Specific Comment #1.

We had stated in the original manuscript that "Stream-gauge data are unavailable for the Seti Khola, hence we validated our model with mapped damage and sediment traces caused by the May 2012 flood." (LL100-101). In the absence of measurements, we use the extents of fluvial sediment deposition during the May 2012 flood as palaeo-stage indicators of the maximum inundation limits. We applied step-backwater hydrodynamic modelling to the 2012 flood and proceeded with this calibrated model to simulate inundation limits of our ten peak discharge scenarios.

General Comment #8:

> 13. At several places in the manuscript, the term 'outburst' flood appears misleading as there is no mention of the temporal dynamics of the flooding event. I request the authors to either justify or remove the 'outburst' term wherever it is mentioned in the manuscript.

We agree with the referee that our simulations do not include a temporal component due to the modelling restrictions described in detail in response to Referee #1's Specific Comment #2. We use the term "outburst flood" to refer to the geomorphic process chain, in which a quantity of water, which was retained behind a natural dam, is released and propagates downstream (Costa and Schuster, 1988). The term "outburst flood", thus, distinguishes this process (chain) from meteorologically-triggered flash floods. We had stressed in LL325-335, and now also in the introduction (see our reply to Referee #1's General Comment #1 and #3), that geomorphic and glaciologic activity in the Sabche Cirque could promote the rapid forming and growth of water bodies (Kargel et al., 2013). Our inundation maps quantify the downstream inundation, i.e. the eventual impacts of this specific process. We now have more comprehensively underlined our study focus on these non-meteorological floods in the introduction, and removed the term "outburst" to be less exclusive about the flood-generating processes involved.

General Comment #9:

> 14. The list of recommendations provided in the manuscript is very generic and applicable to any other case study. I suggest the authors be very specific and structure this section into possible structural and non-structural recommendations for flood management.

We wish to refer the referee to our reply to Referee #1's Specific Comment #10 regarding the recommendations section.

General Comment #10:

> 15. I am not fully convinced with the title of the manuscript over two points- 'outburst', and 'risks'. The query regarding the usage of the former terminology is already mentioned in one of my earlier comments. The manuscript actually does not quantify 'risk', as it does not account for vulnerability as such. The impact assessment addressed in the work is more of an exposure assessment. Therefore, the usage of 'risk' terminology may be avoided in the title and elsewhere in the text. Moreover, the hazard is quantified as the extent of the inundated area, which is a very simple form of indicating a flood hazard.

Please refer to our reply to General Comment #8 regarding the use of the term "outburst flood". Following Referee #1's suggestion, we change the title to "Rare flood scenarios for a rapidly growing high-mountain city: Pokhara, Nepal". We also removed the term "risk" when referring to our assessment and replace it with "exposure".

<u>Specific Comments - Text</u>

Specific Comment #1:

> Line 124: Vertical resolution of ALOS-DEM should be mentioned.

We altered LL124-125 as follows: "Geometric data for our HEC-RAS runs were mainly derived from the commercial ALOS 3D digital elevation model (AW3D DEM), which has a vertical and horizontal resolution of <5 m and was projected to UTM Zone 44N (Fig. 2)."

Specific Comment #2:

Line 127: The authors mention the consideration of around 572 cross-sections of the river channel. A separate figure providing these details may be provided, if possible in the supplementary material.

We thank the referee for this suggestion and added a map displaying the river geometry, i.e. cross-sections, main and tributary reaches, and junctions, used for our modelling in HEC-RAS as supplementary material.

Specific Comment #3:

Line 141: The description of the land-use classes is not required to be added to the text. This may be provided in the form of a separate figure in the supplementary material.

Following Referee #1's suggestion, we summarised the information on LC and LU classes formerly provided in LL139-146 in a new table.

Specific Comment #4:

Line 164: How was the extent of sediment deposition quantified for the May 2012 flood event from the satellite imagery? How this piece of information was useful to the research addressed in this manuscript? Please justify.

Please also refer to our reply to General Comment #7 and Referee #1's Specific Comment #1.

The May 2012 flood represents the only documented flood event to validate our results on. However, as stated in LL100-101, stream-gauge data for the May 2012 flood are unavailable and we had to validate our model with sediment and damage traces, which we interpret as proxys of the inundated area. We manually delineated the extents of flood deposits from orthorectified 5-m resolution RapidEye images acquired on October 18, 2012 - the first cloud-free image following the flood. The sediments deposited by the flood stood out as bright pixels on the otherwise densely vegetated terraces. This use of sedimentary evidence or paleo-stage indicators to reconstruct peak discharges of floods occurring in ungauged river streams has been applied by a number of authors. Retrospective step-backwater hydrodynamic modelling of one-directional steady flow in HEC-RAS – as presented in our study - has been, for example, successfully applied in the Himalayas by Cenderelli and Wohl (2001) or in the Andes by Klimeš et al. (2014). Please also refer to our reply to General Comment #3.

<u>Specific Comments – Figures</u>

Specific Comment Fig. 1:

Please add an appropriate legend to describe what the triangles (stations) represent. An inset map of the elevation\topography of the study area may be included within this figure as well.

We thank the referee for this suggestion and added a legend accordingly (grey triangles mark the locations of settlements mentioned in this study). Following the suggestions of Referee #1, we added contour lines to visualise the topography of our study area.

Specific Comment Fig. 7:

> The description of hazard classes within various land use classes is very difficult to locate. Some sort of different representation may be thought of here to locate the degree of hazard distinctly within land-use classes or create a separate figure for the same.

We adjusted the figure accordingly to improve its clarity.

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