

## ***Interactive comment on “Periodic Glacial Lake Outburst Floods threatening the oldest Buddhist monastery in north-west Nepal” by J. Kropáček et al.***

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Anonymous referee #1 General comment 1: However, one of the main paper contributions (the assessment of the flood hazard at the Halju Village) is undermined by the use of a hydraulic model which is not described in detail and has not been widely used/discussed in flood scientific literature, hampering a critical analysis of the model and the flood modelling results.

Answer: The model is described in more detail in the revised version of the manuscript. It has been tested as European flood service (GIO emer-

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gency services) during the EU project SAFER and f.e. applied to model a possible flash flood in Hunza valley in Pakistan in 2010 (Geomer, 2010) ([http://www.geomer.de/fileadmin/templates/main/res/downloads/Hunza\\_Dam.pdf](http://www.geomer.de/fileadmin/templates/main/res/downloads/Hunza_Dam.pdf)).

The model has been widely used in various flood hazard projects, including modelling of flood scenarios for the Rhine Atlas (ICPR 2001), Odra Atlas (Oderregio-Project) and Elbe Atlas (ELLA-Project). It has also been applied in various studies for Catchment Management Authorities mainly in Germany. Most of these studies were carried out in frames of flood hazard mapping projects for the fulfilment of the EU flood directive. Simulated flood extents and flood depths underwent critical assessment by these authorities, because the results were published and the definition of the 100-year flood extent is legally binding.

Change in manuscript: The section 3.3 have been completely reworked:

General comment 2: The paper also fails in relating data of glacier thinning and retreat (which are well documented in the text) with the lake formation and possible outburst initiation mechanisms.

Answer: We realised that the subtraction of the DEMs shows clearly an elevation decrease in the lake basin area. This appears as a distinct red patch in the Figure 4. This means that a major deepening of the basin took place between 2000 and 2013. We highlighted this finding which documents the relation between the glacier thinning and the lake formation in the manuscript.

Change in manuscript: The deepening of the basin which can be seen in the DEM difference image was shown in the new inlet of figure 4. The chapters describing the lake development and glacier thinning were merged to one chapter titled ‘Glacier changes and evolution of the lake basin’. The following sentences has been added: ‘The detailed image of glacier thinning for the surroundings of the lake basin (Fig) shows a distinct area of a high mass loss in the area of the basin reaching up to around 30 m. This means that the basin developed mainly between 2000 and 2013.’ The

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following sentence was added to the discussion: 'However, from the DEM differencing it is evident that the deepening of the basin must have occurred mainly between 2000 and 2013.'

Specific comments Introduction Page 6939-Line 24: The GLOF acronym was already defined in the abstract. Please restructure the phrase and delete "Glacial Lake Outburst Flood". Answer: The portion of the sentence ' , commonly denoted as Glacial Lake Outburst Floods (GLOFs),' was cancelled.

Page 6940-Line 3: A more pertinent reference than the Mergillio et al (2011) work, concerning the GLOF timing, is the following paper "Ng F, Liu S. 2009. Temporal dynamics of a jökulhlaup system. Journal of Glaciology 55(192): 651–665". Please refer to this work. Answer: The citation was replaced accordingly

Page 6940-Line 15 and 16: Delete "substantial part of" or include supporting data. Answer: The term 'substantial' was replaced by 'large'

Page 6940-Lines 22 and 23: Replace "thus represents a serious threat" by "thus could represent a threat" since there is not enough supporting evidence. Answer: the formulation was changed accordingly.

Page 6940-Lines 26: Delete "The main". Answer: Changed accordingly.

Page 6941-Lines 7,8,9,10,11: This paragraph better fits in the methods section. Please reformulate or delete the phrase.

Answer: We agree to this. The pointed out sentences were either adjusted or removed. Changes in manuscript: 1. The sentence 'Potentially flooded areas are delimited based on hydraulic modelling.' was changed to: 'Potentially flooded areas are delimited considering various scenarios in terms of maximum discharge and surface roughness.' 2. The sentence 'Glacier thinning and mass balance are estimated by subtraction of two Digital Elevation Models (DEMs), and the glacier retreat is mapped using Landsat images.' was removed. 3. the sentence 'The GLOF occurrences are compared to major

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climate parameters derived from the High Asia Reanalysis dataset (HAR), (Maussion et al., 2013).' was changed to: 'Further, we investigated modelled temperature and liquid precipitation during the period of lake filling to understand the driving factors of the flood occurrence.'

Page 6941-Lines 14 and 15: The complete year listing looks awkward. Better write "Between 2004 and 2014 six GLOFs occurred (in 2004, 2006, 2007, 2008, 2009 and 2011)" or similar.

Answer: The sentence was changed accordingly. Change in manuscript: The sentence is now as follows: 'According to interviews with the local villagers, between 2004 and 2014 six GLOFs occurred (in 2004, 2006, 2007, 2008, 2009 and 2011) (Diemebrger et al., 2014).'

Page 6941-Lines 19 and 20: Use magnitude or intensity but not both terms since they are not interchangeable. Answer: Changed accordingly. Change in manuscript: The term 'magnitude' was changed to 'intensity'

Page 6941-Line 22: Replace "eye-witness to the event" by "eye-witness of the event". Answer: Changed accordingly.

Page 6941-Line 24: Since the GLOF is a continuum process better say the "the glacier flood evolved into a debris flow" and not "the glacier flood triggered a debris flow". Answer: Changed accordingly.

Page 6941-Line 25: Delete "at some places". Answer: Changed accordingly.

Page 6941-Line 26: Replace "were considered" by "were taken". Answer: Changed accordingly.

Page 6942-Line 10: This phrase is difficult to understand. You could replace "to cause the flood subsequent to a sudden drainage" by "to cause the reported floods". Answer: Changed accordingly.

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Page 6942-Line 16: Replace "turned out to be drastically limited" by "is limited". Answer: Changed accordingly.

Material and Methods Page 6942-Lines 20 and 21: Replace "By Enhanced Thematic Mapper Plus (ETM+)" by "By the Enhanced Thematic Mapper Plus (ETM+) sensor". Answer: Changed accordingly.

Page 6943-Line 2: Delete "a robust base for". Answer: The part of the sentence 'a robust base for' was cancelled. As the sentence sounded strange, we modified it further. Change in manuscript: 'In order to get a detailed information about lake basin morphology, the empty lake was surveyed . . .'

Page 6944-Line 5: Please comment on the error margin of the formula and its empirical/ physical basis. Check the following work " Ng, F., and H. Björnsson (2003), On the Clague-Mathews relation for jökulhlaups, *J. Glaciol.*, 49, 161–172.

Answer: The information on the nature and reliability of the formula was added.

Changes in manuscript: 1. The word 'empirical' was added to the sentence. 2. The following sentence was added after the formula: 'The formula has a remarkably good fit for a large number of GLOFs but for a single lake the exponent can significantly differ (Ng & Björnsson, 2003).' 3. The following sentence was added to the discussion: 'It should be noted that the maximum discharge of a single event can largely differ from the calculated value as the Clague-Mathews relation is statistically valid for a number of lake outbursts.'

Page 6944-Lines 14,15 and 16: A detailed explanation of the model is required since it has not been widely used/discussed in flood scientific literature. As the model is based on the Manning–Strickler formula, and hence uses data of the hydraulic radius, flood extents in flat areas (like where the Halji Village is located) are not well represented due to the lack of cross sectional area. This fact is acknowledged in the FloodAreaHPC manual. Thus, modeled flood extents could be unrealistic in the Halji Village under-

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mining the modelling effort. Please justify the use of this model and prove that it can realistically model the outburst flood extent (e.g. comparing the model results with past floods and giving an estimation of the error).

Answer: A more detailed explanation of the model will be provided in the revised version of the manuscript. In fact, FloodArea is a raster-based model and unlike 1D hydraulic models like HEC-RAS it does not use cross sectional data to calculate water levels. In the cell-by-cell process employed by FloodArea, flow is exchanged between raster cells and hydraulic radius  $r_{hy}$  is determined for each raster cell in each calculation step (see the figure below, (Fig. 4 in the manuscript)). This means that the model takes into account all terrain information present in the DEM. FloodArea uses the Gauckler-Manning-Strickler formula for uniform flow which is valid for rough fully turbulent flow. Although the model does not solve the full shallow water equations (SWEs), the use of a simplified hydraulic approach as the Gauckler-Manning-Strickler formula is able to deliver realistic results and makes use of the full detail of the terrain data, as Bates & DeRoo (2000) describe in their paper. A general problem of all hydraulic models dealing with the complex phenomenon of GLOFs is the sediment load which is nearly impossible to measure during such an event and the massive change in the riverbed due to erosion and sedimentation processes. Nevertheless, these models have the potential to provide useful estimates of expected flood extents and flow depths. To give recent example for evaluation: In a project for the federal state of Hesse in Germany, a flood which occurred in 1995 was simulated and modelled flood extents were compared to mapped flood extents of the event. The results showed a congruency of 95 % between modelled and mapped flood extents. Main errors in the modelling stem from inaccuracies of the DTM. Even a few centimetres height difference may decide if a depression gets filled or not. The fact that FloodArea uses an instationary model approach minimises these effects compared to a stationary model approach, because only a certain amount of water is able to flow into the adjacent depression during the simulation. Anyhow, the errors caused by potential modelling problems or simplifications are much less than the ones resulting from errors in the ter-

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rain data. Bates, P.D. & De Roo, A.P.J. (2000): A simple raster-based model for flood inundation simulation. In *Journal of Hydrology*, 236 (1), pp 54-77.

Change in manuscript: The section '3.2 Hydrodynamic modelling of GLOF scenarios' was completely reworked.

Page 6945-Line 5: The SRTM data was collected in February 2000 not in 1999. Please correct in all the text. Answer: Changed accordingly.

Page 6945-Line 6: Replace "Geodetic glacier mass balances.....were" by "Geodetic glacier mass balance.... was" since it cover only the 1999-2013 period. Answer: Changed accordingly.

Page 6945-Line 7: Please specify the version of the SRTM used. Answer: The version of the SRTM was added.

Page 6945-Line 16: This sentence is not clear please reformulate. Change in manuscript: The sentence 'For the DEM differencing both DEMs were re-sampled to a resolution of 30 m.' was changed to: 'Both the DEMs were re-sampled to a resolution of 30 m before the subtraction'

Results Page 6945-Line 25: Define the ELA acronym. Answer: The acronym was defined.

Page 6946-Line 9: Delete "in". Answer: Changed accordingly.

Page 6946-Line 5: Replace "was estimated as ranging from" by "ranged from". Answer: Changed to 'was estimated as 5660 m a. s. l. for a nearby glacier'

Page 6946-Line 10: Make clear earlier in the text that the Halji Glacier is a temperate glacier. This will support the discussion given in this paragraph. Answer: Glaciers in the Gurla Mandhata massif were described as cold-based by Owen et al. (2010). To our understanding the Halji Glacier is thermal or poly-thermal. We prefer to avoid a discussion on this topic. Owen, L. A.; Yi, C.; Finkel, R. C. & Davis, N. K. *Quaternary*

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glaciation of Gurla Mandhata (Naimon'anyi) *Quaternary Science Reviews* , 2010, 29, 1817 - 1830

Page 6947-Line 19: Replace "acquired by Thematic Mapper (TM)" by "acquired by the Thematic Mapper (TM) sensor". Answer: Changed accordingly.

Page 6947-Line 20: Replace acquired by Enhanced Thematic Mapper (ETM+) by "acquired by the Enhanced Thematic Mapper (ETM+) sensor". Answer: Changed accordingly.

Page 6948: The section 4.4 cannot be critically analyzed since the reliability of the flood model has not been proven. In fact, was stated in the section 3.3 that the 2011 flood will be compared with the model results but so far this has not been done. In the present form, sections 3.3 and 4.4 are weak, in spite of being a central part of the paper contribution. Answer: With the changes made in the manuscript concerning the flood model (section 3.3, changed to section 3.2 in the new manuscript) we described in detail how the model works and that it is able to deliver realistic results. The discussion of the results has been changed according to changes in model in- and output. The plausibility of the obtained results was checked according to the available data from the field (estimates of flood extents and flow depths from photographs which were taken during the flood, max. sediment particle size to estimate max. flow velocities). This assessment was added to section 4.3 in the manuscript. Change in manuscript: Both mentioned sections (3.2 and 4.3 in the new version of the manuscript) were reworked completely.

Page 6948-Line 24: Delete "severe" since you are not measuring the flood intensity. Answer: Changed accordingly.

Page 6949-Line 1: Data of glacier thinning and retreat are not well linked in the paper with the GLOF events. Please analyze the data of table 4 (in section 4.5) and discuss (in section 5) the potential relationship between the glacier negative mass balance, the lake development and the GLOFs. Answer (the same as the answer to the 'Gen-

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eral comment 2' of the first Referee): We realised that the subtraction of the DEMs shows clearly an elevation decrease in the lake basin area. This appears as a distinct red patch in the Figure 4. This means that a major deepening of the basin took place between 2000 and 2013. We highlighted this finding which documents the relation between the glacier thinning and the lake formation in the manuscript. Change in manuscript: The deepening of the basin which can be seen in the DEM difference image was shown in the new inlet of figure 4. The chapters describing the lake development and glacier thinning were merged to one chapter titled 'Glacier changes and evolution of the lake basin'. The following sentences has been added: 'The detailed image of glacier thinning for the surroundings of the lake basin (Fig) shows a distinct area of a high mass loss in the area of the basin reaching up to around 30 m. This means that the basin developed mainly between 2000 and 2013.' The following sentence was added to the discussion: 'However, from the DEM differencing it is evident that the deepening of the basin must have occurred mainly between 2000 and 2013.'

Page 6949-Line 16: This sentence is not clear "The latter value represents the so far strongest flood in 2011". It seems like more than one GLOF occurred in 2011. Please reformulate. Answer: The sentence was cancelled as a response to the 'Comment 2' of the Referee 3.

Page 6949-Line 23: Delete "striking". Answer: Changed accordingly.

Page 6950-Line 10: Replace "is also depending" by "also depends on". Answer: Changed accordingly.

Page 6950-Lines 3,4,5: This statement is too broad. You could use, for example, the rate of glacier annual retreat to roughly estimate the date when the lake-basin (and GLOF hazard) could disappear.

Answer: To get a realistic estimate of the disappearance of the barrier we measured the glacier retreat in the period 2001-2011 at the outlet of the subglacial channel which is about 50 m. As the ice barrier has 140 m, we roughly estimated the time to the dis-

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appearance of the lake as 30 years. Changes in manuscript: The following was added to the section 4.2: 'and for about 50 m at the subglacial channel outlet.' The following sentence was added to the discussion: 'Assuming the present climate conditions and the same retreat rate of the glacier margin as in the period from 2001 to 2011 the decline of the ice barrier could be roughly estimated as 30 years.'

Page 6950-Lines 6,7: Is not clear to me what do you mean with "still increase due to thermal dissipation of water". Please clarify.

Answer: The third component of the presumed balance had to be mentioned as the glacier flow and melt of the ice only would not be sufficient to maintain the lake basin over a longer time period. The term 'water dissipation' was replaced by more suitable one (thermal erosion) and a brief explanation was added. Change in manuscript: The part 'enlargement of the basin by thermal dissipation' was replaced by: 'enlargement of the basin by thermal erosion of the lake water which absorbs more radiation than the surrounding ice due to its higher albedo.'

Page 6950-Lines 12: Replace "no lake" by "no supraglacial lake". Answer: Changed accordingly.

Page 6951-Lines 10: Replace "presented" by "present". Answer: Changed accordingly.

Tables Table 1: Please specify if the time of the peak discharge is at the glacier or at the village. Answer: It was specified that the peak discharge is at the glacier.

Table 4: Replace "Glacier mean elevation and total ice volume changes as well as annual glacier mass balances measured from DEM differencing of SRTM-3 (1999) to Pléiades (2013)" by "Glacier mean elevation, total ice volume change and annual glacier mass balance measured from DEM differencing of SRTM-3 (1999) to Pléiades (2013)". Answer: Changed accordingly

Table 4: Is not clear to me in what units are you measuring the change in glacier volume. Percentage, m<sup>3</sup> or km<sup>3</sup> are units more frequently used in this context. Answer:

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Here we prefer to keep the unit following for instance Kääb et al. (2012) and Gardelle et al. (2013) as the value of water equivalent in mm can be easily compared with precipitation.

Table 5: Replace "Liquid precipitation amount V " by "Volume of liquid precipitation...".  
Answer: Changed accordingly

Figure 1: Please specify the sensor that captured the November 2011 image.  
Answer: To our knowledge Bing Maps does not provide information about the sensor for a particular image. Figure 2: Add "m.a.s.l" after "(3901)". Answer: Changed accordingly. Further, the diagram was based on wrong data. It had to be reworked completely.

Figure 3b: Indicate the subglacial pathway or other geographic reference to provide a context to the figure. Answer: Entrances to the englacial channels were marked by a star-marker in the figure.

Figure 4: Add an inset with a zoom to the area where the lake develops. At the current scale is difficult to see the area of interest. Answer: The inset illustrating the lake development was added.

Figure 5: Replace "was reinforced" by "were reinforced". Answer: Changed accordingly

Figure 9: Please incorporate the topographic profiles as insets and extend them to cover the whole wide of the village. In this way it will be clear the height difference and distance between the river channel and the populated area. Answer: The figure was modified accordingly.

Figure 9: Specify the coordinate system and make sure that the entire flooded area is clearly shown(e.g. make the village's polygon semi-transparent). Answer: The information on the coordinate system was added. In the new version the flood extents do not overlap the houses. The semi-transparency is therefore not necessary. Change in manuscript: We added the following sentence: 'Coordinate system: UTM, zone 44 N,

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Datum: WGS 84.'

Figure 10: Specify the coordinate system. Answer: Changed accordingly

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Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 6937, 2014.

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