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Interactive comment on "Modeling the Glacial Lake Outburst Flood Process Chain in the Nepal Himalaya: Reassessing Imja Tsho's Hazard" *by* Jonathan M. Lala et al.

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First of all, I apologize for the delay in submitting this review.

Lala et al. present results of a study that investigates cascading processes of an avalanche-triggered GLOF. The authors report on new bathymetric data as well as a numerical simulation chain that combines the different models RAMMS and BASEMENT. Their results represent a valuable contribution to the discourse about the risks related to an outburst of Imja Tsho and provide new insights into GLOF modelling that go beyond this case study. As such, the manuscript is worth publishing and HESS is a suitable journal. Before publication, however, there are few issues that require further work, some of which have been addressed by the first reviewer Simon Cook.

The authors would like to thank the reviewer for his supportive comments. Responses to each are given below.

1. The manuscript is well written. I particularly like the layout of the controversy around the hazardousness of the lake to which the study contributes. However, I think that the discussion section could pick up more of this controversy. Instead, the discussion is very much software related (advantages of BASEMENT, two-phase models (r.avaflow)) which distracts from this controversy. I suggest to restructure the discussion, possibly with subheadings, to keep focus on the controversy.

The discussion was restructured with subheadings, and the following was added under "4.1 Comparison to Other Studies:"

"One reason the results of this study conflict with that of previous GLOF models of Imja Tsho (Somos-Valenzuela et al., 2015; Shrestha and Nakagawa, 2016) is this study modelled the breach of the terminal moraine based on an avalanche entering the lake as opposed to making assumptions regarding the breach or overtopping. Somos-Valenzuela et al. (2015) modelled the breach of the terminal moraine using a combination of empirical and numerical methods, but assumed the breach would be triggered by piping. While piping is theoretically possible, Imja's wide and gently-sloped moraine make this unlikely, especially when one considers Imja's moraine stability compared to other glacial lakes in the region (Fujita et al., 2013). Bajracharya et al. (2007) relied on a similar assumption about internal failure of the moraine and did not consider dynamic causes. The width of the terminal moraine also makes the failure—via overtopping of the moraine—modelled by Shrestha and Nakagawa (2016) unlikely, since even the largest avalanches considered in this study do not fully overtop the terminal moraine.

In contrast to studies that assume dam breaching from internal failures or wave overtopping, studies that relied more on geographic and geomorphic data concluded that Imja Tsho poses little imminent risk and that the lake is currently safe (Fujita et al., 2009; Watanabe et al., 2009; Rounce et al.; 2016), but that expansion up-glacier (eastward) must be monitored to continually assess the risk of mass movement into the lake. The results presented in this study indicate that even if eastward expansion continues, the lake will pose little risk for the next three decades, although regular monitoring of the terminal moraine and up-glacier mass movement trajectories will be needed to continually reassess downstream hazard."

2. Some of the initial conditions related to wave propagation are unclear. Is water that spills over the moraine routed across dry terrain, or is there some initial discharge in Imja Khola? How does flood hazard change if the river is already bankfull during Mon- soon season? Moreover, does the DEM cover the area down to Dingboche? Was the DEM preprocessed and hydrologically corrected? In a recent study, we have shown that hydrodynamic models are quite sensitive to pits in the DEM as they become subsequently filled during flood-wave propagation (Bricker et al., Mountain Research and Development, 37, 5-15). Is it possible that the strong attenuation of the flood wave is due this issue? Moreover, what is the hydrograph volume that leaves the lake and what is its proportion to overall lake volume. Is there some incision into the moraine dam that lowers the lake or is the hydrograph volume merely the water that overtops the dam crest?

Because the initial discharge of the Imja Khola is small, it is not taken as an initial condition in the model, although there is some discharge present once the model is running due to the difference in elevation between the lake surface and the lake outlet. Even during the monsoon season, however, discharge in the Imja Khola at Dingboche is only around 4-6 m^3 s^{-1} (Rajkarnikar, 2013)—less than 4% of the peak discharge from the GLOF flood. Dingboche sits on a terrace ~10-20 m above the river bed, and the river is never bankfull even during the monsoon season. For this reason, monsoon discharge was assumed to have a negligible effect on GLOF flood hazard. The following was added to section 2.3.4:

"Initial discharge from Imja Tsho was assumed to be negligible, since peak monsoon

discharge at Dingboche of 4-6 m^3 s^{-1} was less than 4% of the peak discharge from the GLOF flood wave (Rajkarnikar, 2013; see Results, Figure 8)."

The DEM covers the entire area of the simulation; only the bathymetry came from a different source (field survey). The DEM was preprocessed through outlier filtering (any value exceeding $\pm$120 m, or 3 standard deviations difference from a SRTM DEM used as a reference; see King et al., 2017), but it was not specifically hydrologically corrected. However, the DEM was converted from a raster to a triangulated irregular network (TIN) for use in the BASEMENT simulation, which acted as a smoothing method. The few small raster sinks in the floodplain (four in the inundated areas between the outlet and Dingboche, none greater than 150 m^2 in area) were thus effectively filled.

For a large avalanche in 2045, the volume of water leaving the lake is negligible compared to the total lake volume, suggesting that catastrophic damage to the moraine is unlikely. The moraine was not fully overtopped and hence discharge was funneled through the outlet channel of the moraine. The following sentences were added to section 3.3:

"In the first 2000 s of the simulation (i.e., before discharge lowers to ~5 m^3 s^{-1}), the total volume of water leaving the lake was approximately 251,000 m^3 for the MPM simulation and 166,000 m^3 MPM-Multi simulation—less than 0.3% of the total present lake volume (88 million m^3). This is notably less than the amount of avalanche material entering the lake (approximately 720,000 m^3; Table 5). Moreover, the lake's surface elevation remains slightly above its original elevation at the end of the simulation period (by approximately 0.25 m), suggesting that erosion of the moraine was not sufficient to allow the lake to drain quickly, and may have even allowed the lake to store more water."

"In both cases, the moraine was not fully overtopped, and erosion was confined to the outlet channel."

3. I think that the differences in the Heller-Hager model and the wave heights from

BASEMENT should be discussed in the discussion section. The calibration of the model using the analytical Heller-Hager model seems admissible, although it is far from elegant. Can this be overcome somehow?

The Heller-Hager model was used as a calibration model because it produced wave heights similar to that of FLOW3D, which was shown by Somos-Valenzuela et al. (2016) to be a more robust approach to modeling lake wave dynamics since it is not as susceptible to wave attenuation, which is present in 2-D shallow water equation (SWE) models like BASEMENT. One of the goals of this study, however, is to simply the process outlined by Somos-Valenzuela et al. (2016) by modeling both the lake wave and the downstream impacts with BASEMENT, rather than using the more complex and computationally intensive FLOW3D model for the lake wave. Since BASEMENT is a 2-D SWE model, the lake wave heights are susceptible to strong attenuation that would lessen the simulated impact downstream. Therefore, to account for this strong attenuation, the wave heights from the Heller-Hager model were used to adjust the BASEMENT simulations. The following was added in section 2.3.1 to clarify the use of the Heller-Hager method:

"...it has been used to successfully model some real-world events and performs well in characterizing the impulse wave within the lake, which makes it a useful as a calibration measure for more complex hydrodynamic models (Somos-Valenzuela et al., 2016). Moreover, it is not as susceptible to wave attenuation inherent in 2-D SWE models such as BASEMENT, making it an ideal calibration measure that is both simple and accurate."

Specific comments

2, 13: Remove "catastrophic". It is the chain of events and impacts that make these events catastrophic. But per se, they are not catastrophic.

"catastrophic" removed

5, 17: To my knowledge, Fischer et al.'s study adresses the European alps and not the Everest Region.

Noted. Statement has been deleted.

6, 17: Is this truly a <4 m resolution DEM, or is it a DEM with an accuracy of ~4 m, as stated in the referenced paper (King et al., 2017)?

The resolution of the DEM is 3.57 m, but to maintain consistency with the text of King et al. (2017) the manuscript was corrected to "~4 m"

8, 19: BASEMENT

corrected to "BASEMENT"

13, 21: Heller-Hager

corrected to "Heller-Hager"

15, 4: Debris discharge: Please clarify what you mean by this term. Sediment discharge? Or sediment and water discharge combined?

Clarified to "Combined sediment and water discharge;" clarification also made in Figure 8 caption.

Fig 8 requires labelling (A-C) of the panels.

Figure 8 panels labeled to match that of Fig. 7 (Figures 9 and 8, respectively, in revised manuscript)

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