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Interactive comment on "Glacier change and glacial lake outburst flood risk in the Bolivian Andes" *by* Simon J. Cook et al.

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General

In agreement with the editorial comments by Etienne Berthier and the comments by Mauri Pelto I consider this contribution to be a welcome and interesting study about a less well-documented regional development. As the two mentioned colleagues discussed the questions of remote sensing, glacier mapping and hydrology, my comments can focus on questions of hazard and risk assessments. My recommendations aim at encouraging the authors to more critically reflect their techniques and formulations concerning people-related hazards and risks. Scientific hazard and risk studies are policy-relevant and require aspects of transparency and honesty to be especially critically reflected.

Hazard and risk aspects

Equations (2) and (3) are used for area-based estimates of lake volumes, which are then applied as input for calculating peak-discharge values, which in turn are taken as indicators of hazard potentials. There are three fundamental problems related to the application of such unfortunately quite popular equations: Volume-area relations are unnecessary area-area self-relations, the preciseness of the numerical values used in the regression equations is disproportionate with respect to the accuracy and reliability of the results obtained and the statistics deal with mean instead of extreme values which is an uncommon and problematic procedure in hazard consideration.

Lake volumes are determined by multiplying measured lake areas with measured and averaged/integrated lake depths. Correlating lake volume with lake area, therefore, means to correlate a mathematical product with one of the factors from which it had been calculated. Correspondingly, predicting lake volumes from lake areas means to essentially predict lake areas as used for volume calculation from themselves. Why should we do this? Because "many do it" (including myself in earlier papers)? Because the statistics and scatter plots look better? Or because the knowledge on how lake volumes are determined is lost? I strongly recommend to strictly avoid unnecessary volume-area self-relations but to use the straightforward relation between the originally determined lake areas and lake depths. This straightforward approach produces exactly the same results but is transparent and honest in that it not only shows what is measured and what is calculated but especially also illustrates the large scatter in the relation between the two measured variables and shows the resulting enormous uncertainty in the estimated values as well as in all further values (here volumes, peak discharges) derived from them. In fact, the morphometric analysis of glacier-bed overdeepenings where lakes may form clearly shows that large features can be shallow and small features can be deep (Haeberli et al. 2016). This should be clearly said in order to avoid unrealistic expectations: Orders of magnitude for lake volumes can at best be estimated empirically. Correspondingly, the excess preciseness of the numerical values used in equations (2) and (3) derived from statistical regression and used in such order-of-magnitude estimates is disproportionate and provides a misleading impression of the accuracy and reliability which can be reached in reality. In addition to these two problems, equations (2) and (3) also have the problem that they represent medium-value statistics while hazard assessment must be made with extreme-value statistics for worst-case considerations.

Equation (4) is an example and outcome of such reflections: It avoids over-sophisticated and over-precise mean-value and self-relation statistics but enables in a perfectly transparent way the realistic estimation of empirical extremes in a simple way even without any computer: the fact that the right-hand side of this equation is written as 2V/1000 instead of V/500 helps to make its application as easy as possible, even in the field or for non-scientists. This simplicity and transparency also makes it clear to scientists as well as to stakeholders or even the public where the limits are of our knowledge, understanding and ability to predict numbers of unmeasured lake volumes for practical applications in the real world.

Extreme peak-discharge values as estimated, for instance, by equation (4) refer to worst-case events. In the case of glacial and periglacial lakes, such extreme peak values can result from sudden-break mechanisms of dams consisting of broken ice from ice avalanches or glacier surges, from massive erosion and debris-flow formation in connection with moraine breaching, or from squeezing-out of more or less entire lakes by large ice/rock avalanches. This is again essential to be made clear. Worst-case scenarios with such extreme peak discharge values relate to low-frequency/high-magnitude events. Dealing with corresponding hazards from events with extremely low probability but also with extreme damage potential are a special challenge for policy making with regard to risk acceptance and risk management. Most outburst processes such as, for instance, progressive enlargement of sub-glacial channels produce far smaller peak discharges. Careful wording of worst-case scenarios is necessary in order to avoid adverse psychological and economic effects which can exceed the po-

tential damage occurring in reality or perhaps even not occurring at all.

The continued glacier retreat indeed tends to reduce glacier sizes and, hence, areas and volumes of new lakes forming as a consequence of ice vanishing. It also reduces direct ice-contacts of lake water with calving fronts. This does, however, not necessarily reduce the hazard potential. The more the glaciers retreat the closer new lakes form to steep walls of icy peaks with degrading permafrost and long-term reduction of slope stability. The corresponding scientific literature is easily accessible today. In Bolivia, permafrost can be expected at altitudes above about 5000m a.s.l where the 0°C isotherm is found (cf. Carey et al. 2012). This may be a lesser influence on the hazard situation in the investigated region but must be correctly mentioned and treated. De-buttressed slopes and slopes with degrading permafrost are the two situations with the most rapid and important change in long-term rockfall disposition.

Minor technical notes

1-24: “contain” not contains

2-04: The term “climate warming” is popular but not scientifically correct and should better be replaced by something like “climate change”, “global warming” or “atmospheric temperature increase”: Climate is defined as an average of meteorological parameters (not only temperature) over extended time periods (usually decades). As such it cannot “warm” (the permafrost can warm).

2-26: Carey et al. (2012) and Haeberli et al. (2016; as mentioned in the text) could be added here concerning the recent example of Laguna 513 in the Cordillera Blanca).

4-15 and 5-first paragraph: The 500m limit is highly subjective and not really reliable: Ice avalanches over firn/ice surfaces can have trajectory lengths 3 times the drop height and rock or rock/ice avalanches can by far exceed such limits. If the authors prefer to stick to their number they should comment on it accordingly. The phenomenon of permafrost should be mentioned here.

5-9: The involved processes of outburst triggering and flood propagation in the torrent below the lakes are of primary importance concerning potential damages and corresponding hazard potentials, rather than lake area or lake volume. This should be mentioned.

5-13/14: This assumption is again delicate: squeezing out of a small lake by an ice or rock avalanche may cause far-reaching floods with high damage potential.

5-23: Trajectory slopes have so far been used rather than simple distances. Process chains can affect infrastructure over much longer distances than 20 km. Again: A problem of low frequency/high magnitude events. Most events will remain far within distances of 20 km but in the worst case 20 km may by far not be enough.

7-33: Eliminate "increase" after 72%.

8-10/14: make clear that these values refer to highly unprobable worst-case scenarios.

11-01: ". . . decreased in such cases . . ."?

11-23: a more recent reference would be Linsbauer et al. (2016)

11-28: eliminate one full stop after ". . . infrastructure."

12-28/29: mention that these values are worst-case scenarios and add that the "higher stability" of lakes in rock basins may be questioned in case of possible impact waves produced by rock/ice avalanches from de-buttressed slopes or slopes with degrading permafrost (cf. especially Deline et al. 2014).

Table 2: Lake volumes are not extreme values but peak discharges are extreme values from worst-case scenarios. At least point to this discrepancy and discuss it in the text

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