Modeling permafrost occurrence, glacier-bed topography and possible future lakes for assessing changing hazard conditions in cold mountain regions

Wilfried Haeberli, Florence Magnin, Andreas Linsbauer

Modeling permafrost occurrence, glacier-bed topography and possible future lakes for assessing changing hazard conditions in cold mountain regions

Wilfried Haeberli[1]
Florence Magnin[2,3]
Andreas Linsbauer[1,4]
[1]*Geography Department, University of Zurich, 8057 Zurich, Switzerland*
[2]*Department of Geosciences, University of Oslo, Blindern, 0316 Oslo, Norway*
[3]*EDYTEM Lab, Université Savoie Mont Blanc, CNRS, 73376 Le Bourget du Lac, France*
[4]*Department of Geosciences, University of Fribourg, 1700 Fribourg, Switzerland*

Abstract

The rapid transformation of glacial into periglacial mountain landscapes under conditions of continued global warming can cause new and locally severe changes in hazard and risk conditions. A special focus must be on systematically increasing risks due to far-reaching flood waves or debris flows caused by rock/ice avalanches into new lakes at the foot of steep slopes with decreasing stability due to permafrost degradation and/or glacial de-buttressing. Modeling permafrost occurrence and glacier-bed topography provides important information for anticipating critical future situations.

Keywords: global warming, mountain permafrost, glacier beds, new lakes, rock/ice avalanches, natural hazards.

Under conditions of continued global warming in cold mountains, most glaciers tend to disappear within decades while the degradation of permafrost on exposed slopes can take centuries. Glacial landscapes are therefore rapidly and for extended future time periods transforming into periglacial landscapes with permafrost still existing but in strong thermal disequilibrium. Modeling such new landscapes is an important emerging research field (Haeberli, 2017). One key aspect relates to changing hazard conditions related to decreasing slope stability due to permafrost degradation and glacial de-buttressing, possibly causing impact/flood waves from rock/ice avalanches into new lakes (Haeberli *et al.*, 2017). Anticipation of critical future situations requires permafrost and glacier-bed modeling (Colonia *et al.*, 2017; Linsbauer *et al.*, 2016; Magnin *et al.*, 2017). Figure 1 shows an example from an ongoing study in the Mont Blanc region. Rock wall temperature was mapped based on a statistical model fitted with rock surface temperature measurements from the entire Alpine range (Boeckli *et al.*, 2012) implemented with high-resolution (4 m) topography and local air temperature data (Magnin *et al.*, 2015). Glacier-bed topography was calculated using the GlabTop model (Linsbauer *et al.*, 2012) with a 20 m resolution DEM (upscaled 4 m DEM) and digitized branch lines drawn within glacier outlines mapped by Gardent *et al.* (2014). Modeled overdeepenings were checked against morphological criteria (slope change, crevasse patterns, lateral narrowing; Frey *et al.*, 2010). It can be seen that possible future lakes will not only form at the foot of large and steep permafrost slopes, for instance at Aiguille Verte and Les Droites, but also close to oversteepened and glacially de-buttressed lateral glacier-bed slopes.

New lakes exposed to potential rock/ice avalanches are multipliers of hazard and risk in the region. Possible catastrophic process chains including impact waves and secondary phenomena such as far-reaching flood waves and debris flows must be considered using corresponding sequences of numerical models (Schneider *et al.*, 2014, Somos-Valenzuela *et al.*, 2016, Worni *et al.*, 2014). The probability of catastrophic events cannot be quantified but undoubtedly increases with further glacier retreat and related formation of new lakes in the valley, and with continued permafrost degradation and stability reduction in the surrounding icy peaks. Reflection about possible protective measures should better start now than later, because simple solutions may not exist and major investments and efficient engineering work such as retention structures may be difficult and take time. Aspects of landscape protection and options for hydropower production, water supply and tourism should also be considered. A matrix-type analyses of potential synergies but also of potential conflicts as part of participative planning can be recommended (Haeberli *et al.* 2016).

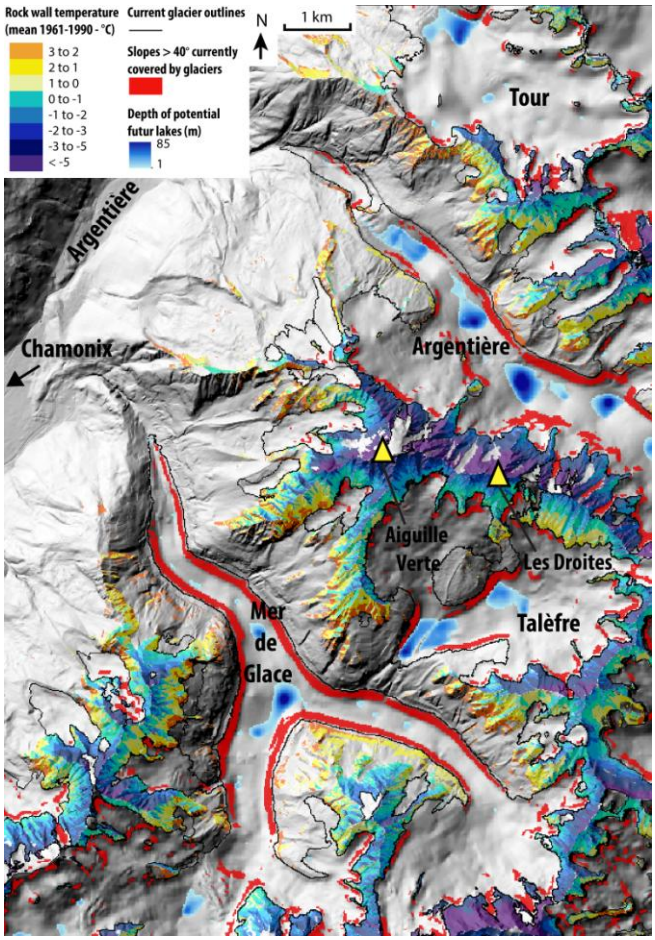

Figure 1: Mer de Glace, Glacier d'Argentière and surroundings in the Mont Blanc region, French Alps: Model calculation of present rock-wall temperatures, glacier-bed topography with oversteepened and overdeepened parts of glacier beds. With the vanishing of the glacier ice, the oversteepened parts of the glacier beds will become de-buttressed and glacier-bed overdeepenings may transform into possible future lakes when becoming exposed.

Acknowledgments

We thank M. Gardent for providing glacier outlines and related information.

References

Boeckli, L., Brenning, A., Gruber, S. & Noetzli, J. 2012. Permafrost distribution in the European Alps: calculation and evaluation of an index map and summary statistics. *The Cryosphere* 6: 807–820. doi:10.5194/tc-6-807-2012

Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C. & Cochachin, A., 2017. Compiling an inventory of glacier-bed overdeepenings and potential new lakes in de-glaciating areas of the Peruvian Andes: Approach, first results, and perspectives for adaptation to climate change. *Water* 9, 336. doi:10.3390/w9050336.

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. & Paul, F., 2010. A multi level strategy for anticipating future glacier lake formation and associated hazard potentials. *Natural Hazards and Earth System Science* 10: 339-352. doi:org/10.5194/nhess-10-339-2010

Gardent, M., Rabatel, A., Dedieu, J.-P. & Deline, P. 2014. Multitemporal glacier inventory of the French Alps from the late 1960s to the late 2000s. *Global and Planetary Change* 120: 24-37. doi.org/10.1016/j.gloplacha.2014.05.004

Haeberli, W., 2017. Integrative modelling and managing new landscapes and environments in de-glaciating mountain ranges: An emerging trans-disciplinary research field. *Forestry Research and Engineering: International Journal* 1(1). doi: 10.15406/freij.2017.01.00005 442.

Haeberli, W., Buetler, M., Huggel, C., Lehmann Friedli, Th., Schaub, Y. & Schleiss, A.J., 2016. New lakes in deglaciating high-mountain regions – opportunities and risks. *Climatic Change* 139(2): 201-214. doi:10.1007/s10584-016-1771-5

Haeberli, W., Schaub, Y. & Huggel, C., 2017. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* 293: 405-417. doi:10.1016/j.geomorph.2016.02.009

Linsbauer, A., Frey, H., Haeberli, W., Machguth. H., Azam, M.F. & Allen, S., 2016. Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya–Karakoram region. *Annals of Glaciology* 57 (71): 119-130. doi:10.3189/2016AoG71A627

Linsbauer, A., Paul, F. & Haeberli, W., 2012. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. *Journal of Geophysical Research* 117: F03007. doi:10.1029/2011JF002313

Magnin, F., Brenning, A., Bodin, X., Deline, P. & Ravanel, L. 2015. Modélisation statistique de la distribution du permafrost de paroi : application au massif du Mont Blanc. *Géomorphologie : relief, processus, environnement* 21 : 145-162, doi.org/10.4000/geomorphologie.10965

Magnin, F., Josnin, J.-Y., Ravanel, L., Pergaud, J., Pohl, B. & Deline, Ph., 2017. Modelling rock wall permafrost degradation in the Mont Blanc massif from the LIA to the end of the 21st century. *The Cryosphere* 11: 1813–1834. doi:org/10.5194/tc-11-1813-2017

Schneider, D., Huggel, C., Cochachin, A., Guillén, S. & García, J., 2014. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. *Advances in Geosciences* 35: 145–155. doi:10.5194/adgeo-35-145-2014

Somos-Valenzuela, M.A., Chisolm, R.E., Rivas, D.S., Portocarrero, C. & McKinney, D.C., 2016. Modeling glacial lake outburst flood process chain: The case of Lake Palcacocha and Huaraz, Peru. *Hydrology and Earth System Sciences* 20: 2519–2543. doi:10.5194/hess-20-2519-2016

Worni, R., Huggel, C., Clague, J.J., Schaub, Y. & Stoffel, M., 2014. Coupling glacial lake impact, dam breach, and flood processes: a modeling perspective. *Geomorphology* 224: 161–176. doi.org/10.1016/j.geomorph.2014.06.031