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# Computer simulations of complex cascading landslide processes: what can we do and what can we learn?

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High-mountain areas in a warming climate are susceptible to various types of rapid landslides, which may be related to retreating glaciers, the associated glacial lakes, thawing permafrost, or a combination of various effects. Particularly in those situations where water bodies or entrainment of snow, ice, or debris are involved, initial movements may evolve into complex process chains, transporting material over tens of kilometres down to the populated valleys within an hour or even much less. The present work aims at exploring the potential of simulating such cascading mass flows, using the two-phase flow model implemented with the computational tool r.avaflow.

We consider two well-documented multi-lake outburst floods in the Cordillera Blanca, Peru, and two catastrophic mass flows from Nevado Huascarán in the same mountain range in 1962 and in 1970. We now focus on the latter events: both in 1962 and in 1970, rock-ice avalanches were triggered from the steep west face of the northern summit of Huascarán and, through entrainment of glacier ice, snow, and glacial deposits, evolved into destructive avalanches of debris and ice. Whereas the immediate impact of the 1962 event was constrained to a large debris cone, part of the much larger 1970 flow overtopped a more than 100 m high hill (Cerro de Aira) and completely destroyed the town of Yungay, demonstrating a dramatic effect of event magnitude on connectivity.

The sets of input parameters are optimized independently for each of the two events, in order to achieve a maximum degree of empirical adequacy of the simulation results in terms of correspondence with the observed impact areas, deposited volumes, and travel times. Parameter optimization is successful in both cases, and a high level of correspondence between the simulation results and the observations is achieved. However, switching the optimized parameter sets (i.e. applying the set optimized for the 1962 event to the 1970 event, and vice versa) unveils one of the major challenges in the field of mass flow simulation: the correspondence between simulation results and observations is poor as the optimized parameter sets are not transferable to another event of a different magnitude, even though the general characteristics of the events are comparable. Most notably, overtopping of Cerro de Aira is predicted for the 1962, but not for the 1970 event.

The patterns among the simulated deposition volumes in the area of Yungay obtained with various combinations of the key model parameter values reveal the importance of the threshold effect of overtopping of Cerro de Aira. Comparable phenomena are partly observed for the simulated lake outburst floods, where the threshold effect of dam overtopping as a response to landsliding into a given lake determines whether there is an impact down-valley or not.

Considering the high sensitivity of the simulation results to uncertain parameters as it is demonstrated in the present contribution, we conclude that the use of likelihood measures or scenario analyses is an absolute requirement when trying to anticipate future complex mass flows for the purpose of risk management.