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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Reconstruction of the 1941 GLOF process chain at Lake Palcacocha (Cordillera Blanca, Perú)" *by* Martin Mergili et al.

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This is an interesting and useful paper that serves two important functions. Firstly, it provides a back analysis of the 1941 GLOF process chain from Laguna Palcacocha, Peru, that helps an understanding of the physical processes associated with the event. Secondly, it is a useful demonstration or r.avaflow software that is fast becoming more widely applied for such studies.

The only comment I would make in this discussion is to expand a little on the detail behind the Laguna 513 situation between 1988 and 1994 as many papers that cite this lake do not report the full story and it merits telling again. Details of the remediation work undertaken have been described by Reynolds, J.M. 1998. Managing the risks of

glacial flooding at hydro plants. Hydro Review Worldwide, 6(2):18-22; and by Reynolds, J.M., Dolecki, A. and Portocarrero, C. 1998. The construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru. In: Maund, J. & Eddleston, M. (eds.) Geohazards in engineering geology. Geological Society Engineering Group Special Publication No. 15, pp. 41-48.

In essence, in late 1988, surveying undertaken by local engineers identified that the small moraine dam impounding Lake 513 was ice cored and that this ice core was subsiding through ablation by $\sim$11 cm/month. It was a simple calculation, therefore, to estimate that by early 1989, the subsidence would have reduced the freeboard to zero and worse, would have resulted in the moraine dam failing and being eroded leading to an outburst flood. The local engineers, led by Cesar Portocarrero, identified that siphoning would be sufficient and practical to reduce the lake level by 3 m or so to alleviate a possible outburst. However, they had insufficient funds to purchase the necessary siphons. Two days before Christmas 1988, Cesar phoned me in the UK from Peru to ask if I could help. A few phone calls and several hours later I had managed to persuade the British Embassy in Lima to provide the necessary funds. Consequently, within a couple of weeks the siphons had been installed and the lake level lowered.

In 1991, a small ice avalanche, thought to have originated from the hanging glacier perched above the lake, fell into the lake producing a small displacement wave. However, this was sufficient to breach the remains of the moraine dam and produce a small outburst flood. It had the consequences of lowering the water level down to and exposed a solid rock bat that had been beneath the terminal moraine dam. The new water level was by this time only just below the rim of the rock bar.

Ing. Portocarrero began to design a more permanent mitigation scheme of tunnelling through the rock bar to lower the lake by 20 m. In 1993, having been informed of his design, it became apparent that the water hydrostatic pressure under 20 m plus head of water could rupture the discharge portal end of the proposed tunnel leading to a greater failure of the distal flank of the rock bar. With emergency funding provided by the British

Government, in late 1993 Reynolds and Dolecki visited the site operations with Ing. Portocarrero. We came up with a scheme for which the equipment was already on site that required the excavation of a tiered suite of tunnels whose inflow portals were set 5 m vertically apart, with the uppermost tunnel being opened first, to lower the lake level down by 5 m; then the second tunnel, for a further 5 m lowering. Explosives failed to detonate for the break through for the third tunnel, so it was decided to go for a 10 m breach through to the lowermost tunnel, which was established safely and the lake was successfully lowered by 20 m, thereby creating a freeboard against avalanche push waves and displacement waves in the case of further avalanche activity. The thinking at that time was that an ice avalanche would most probably originate from the ice cliff associated with the perched hanging glacier immediately above the upstream end of the lake.

The rock/ice avalanche that occurred in 2010 was from the uppermost flanks of the backwall above the lake. This was then when it was realised that this avalanche might have been triggered by thawing of permafrost where the rock face was exposed. Thankfully, having lowered the lake level by May 994 by 20 m, when the avalanche occurred in 2010, the exposed rock bar with 20 m of freeboard accommodated most of the 28-m high avalanche push wave, with only a residual amount overtopping the rock bar. Had the further remediation not have been undertaken, the consequences of this 2010 would most likely have been far more tragic, with possibly as many as 5-6,000 fatalities, as defined by the local mayor. Whilst the 2010 GLOF/alluvion caused damage, especially to the outskirts of the town, there were no casualties.

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