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Supplement of

**Anthropogenic climate change and glacier lake outburst flood risk:
local and global drivers and responsibilities for the case of
lake Palcacocha, Peru**

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1 Supplementary Material

2
3 In this document further details on the methods applied are provided.

4 5 **GLOF hazard modeling and analysis**

6 A glacial lake outburst typically consists of a chain of interacting mass movement processes. Coupled
7 numerical models, simulating the cascade of involved mass movement processes, allow for a
8 quantitative and transparent hazard analysis and mapping of such complex processes (Schneider et al.,
9 2014; Worni et al. 2014). For the analysis of GLOF hazards from lake Palcacocha we here rely on the
10 work presented by Frey et al. (2018) who simulated different GLOF scenarios with numerical mass
11 movement models for three different glacier lakes in the Quillcay catchment, including lake Palcacocha.
12 Their approach follows earlier modeling studies performed at lake Palcacocha by Somos-Valenzuela et
13 al. (2016), and is in line with the recommendations for glacier hazard assessments from the Standing
14 Group on Glacier and Permafrost Hazards in Mountains (GAPHAZ) of the International Association of
15 Cryospheric Sciences and the International Permafrost Association (IACS/IPA) (GAPHAZ, 2017). In
16 the following, the methodological basis of this hazard analysis map is summarized, further details and
17 results can be found in Frey et al. (2018).

18
19 For the case of lake Palcacocha, a major ice or combined rock-ice avalanche is considered as the only
20 potential trigger mechanism of a GLOF. Klimeš et al. (2016) showed, that other mass movement
21 processes such as landslides from the inner flanks of the steep Little Ice Age moraines surrounding lake
22 Palcacocha are very unlikely to reach a magnitude which would provoke a major overtopping wave.
23 Considering the structural hazard prevention works, including the reinforced dams and the fixed outlet
24 channel, other critical processes, such as heavy precipitation, seepage and piping in the dam, can as
25 well be excluded as potential GLOF triggers. However, the steep glacierized faces of Mount Palcaraju
26 and Pucaranra have the potential to produce ice avalanches of up to $3 \times 10^6 \text{ m}^3$ in the worst case, which
27 would trigger major impact waves in lake Palcacocha and lead to the overtopping of large volumes of
28 water (cf. Somos-Valenzuela et al., 2016).

29
30 Modelled GLOF scenarios for lake Palcacocha are therefore based on a susceptibility analysis for ice
31 and rock-ice avalanches originating from the glaciated headwalls in the surrounding of the lake. Based
32 on an analysis of topography, crevasse patterns and estimated ice thicknesses, following an approach
33 proposed by Schaub et al. (2015), three avalanche scenarios of high, medium and low probability were
34 defined. For each of the three scenarios, the entire chain of mass movement processes was then
35 simulated with corresponding numerical models: Rock-ice avalanches were modeled using the
36 RAMMS model (Christen et al., 2010); impact wave generation and propagation, run up at the dam and
37 overtopping hydrographs were estimated with the hydrodynamic models IBER (IBER, 2010) and
38 FLOW3D (Flow Science, 2012) and cross checked with empirical estimation approaches developed by
39 Heller et al. (2009). Resulting hydrographs of the overtopping waves served as an input for the
40 modelling of the eventual GLOF, which was again conducted using the RAMMS model. These results

41 were directly compared to the results from Somos-Valenzuela et al. (2016), obtained with the FLO-2D
42 model. For each scenario, GLOF inundation heights were converted into intensity maps with high and
43 medium intensity if flow height is above or below 1m, respectively, and eventually translated into
44 hazard levels, according to international and national standards (CENEPRED, 2015; GAPHAZ, 2017;
45 Hürlimann et al. 2006; Raetzo et al., 2002).

46
47 A critical point in the process chain described above is the possibility of retrogressive erosion at the
48 dam, which could initiate the formation of a breach in the moraine dam. In this case, much larger
49 volumes of water could be released, leading to an extreme GLOF volume, as it was the case in the 1941
50 outburst of lake Palcacocha. To assess the susceptibility of the Palcacocha moraine for breach
51 formation, Somos-Valenzuela et al. (2016) applied the BASEMENT model (Vetsch et al., 2018; Worni
52 et al., 2012) for the simulation of erosional processes involved in the formation of a breach. Somos-
53 Valenzuela et al. (2016) conclude that breach formation at the moraine dam of lake Palcacocha is very
54 unlikely. However, in order to include this unlikely processes as a worst-case scenario, a GLOF
55 resulting from a dam failure at lake Palcacocha was modeled. Resulting affected areas were translated
56 into low hazard level. This corresponds to the Swiss standard of assigning worst-case extreme events
57 with very low probabilities to the lowest (residual) hazard level, irrespective of intensity levels (FOEN,
58 2016; Schneider et al. 2014), and at the same time fulfills the Peruvian standard of four hazard classes
59 (CENEPRED, 2015).

60
61 The hazard map by Frey et al. (2018) represents the GLOF hazard posed by three different lakes in the
62 Quillcay catchment, which also includes lakes Tullparaju and Cuchillacocha in addition to Palcacocha.
63 In turn, the hazard analysis and map shown in Figure 5 represents the GLOF hazard emanating from
64 lake Palcacocha only.

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68 **Qualitative research methods on socio-economic risk drivers**

69 The analysis of socio-cultural and institutional factors incorporates qualitative data gathered during 20
70 months of ethnographic fieldwork in the Cordillera Blanca between 2017 and 2018. Ethnographic
71 research involves building long-term relationships to gain an in-depth understanding of particular
72 people's ways of life. The co-author Noah Walker-Crawford lived and participated in daily life with
73 farming communities outside of Huaraz and spent extended periods of time following the practices of
74 institutional actors and residents in the city. Research with rural farmers who also live in urban areas
75 designated as dangerous was a particular focus of this study. Information was gathered primarily
76 through informal discussions with informants on their attitudes towards social and environmental
77 change. This data emerged through extended participant observation during which the researcher
78 established relations of trust and gained broader contextual insight into daily life in a changing Andean
79 environment. This involved living with a local family in an Andean village, participating in agricultural
80 work and following government projects to reduce risk from Lake Palcacocha. Gathering information
81 on institutional processes also involved the participation in planning and implementation meetings with

82 different governmental and non-governmental institutions. Semi-structured interviews with key
83 informants supplemented data gathered through informal discussions.

84

85 Further qualitative evidence comes from the analysis of written materials, both published and
86 unpublished. Archival research was conducted in government and non-governmental archives, where
87 unpublished reports, correspondence, policy briefs, maps, engineering analyses, permits, brochures,
88 pamphlets, and other related materials were collected and analyzed. Newspapers, magazines, and other
89 locally published materials were also consulted in Callejón de Huaylas (Huaraz region) and Lima
90 libraries, newspaper offices, government offices, and company offices. Published sources appearing on
91 the Internet were also consulted, particularly news sources published in Peru in Huaraz and Lima,
92 among other locations. Finally, published scholarship was also consulted and reviewed. In all of these
93 cases, the material was limited in scope and quantity because there is relatively little published about
94 the human dimensions of Lake Palcacocha and few archival, library, or other unpublished sources that
95 discuss the lake or related issues.

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