

## **Climate change and diverse dimensions of glacial lake outburst floods (GLOFs): Lake Palcacocha case study, Peru**

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Post-Little Ice Age (LIA) climate change has led to worldwide glacier retreat, formation and evolution of glacial lakes, occasionally followed by glacier lake outburst floods (GLOFs). Hundreds of GLOFs are documented throughout the 20th and 21st century, of which a certain number that caused massive downstream destruction and up to thousands of lives lost. Management of GLOF hazards and risks has typically been a local concern, focusing on the implementation of specific technical and engineering measures.

Recently, however, researchers have realized that the complexity of both the risks and the socio-environmental context requires a broader understanding and response beyond the more typical local perception and management. The growing cumulative greenhouse gas (GHG) emissions, for instance, increase the anthropogenic contribution to glacier retreat, lake formation and growth and eventually to GLOF. GLOF hazard and risk management is inherently linked to the global scale from this perspective. It implies that additional important dimensions enter the debate, including ethical and legal questions about the responsibility for damage and loss due to GLOFs.

Here we analyze the conditions at an emblematic case in Peru's Cordillera Blanca, which has made international headlines repeatedly since it first generated one of the world's most deadly GLOFs in 1941 to its present-day growth and instability. Situated upstream from the regional center of Huaráz (population ~120,000), Lake Palcacocha has attracted significant attention in recent years within Peru and at an international level. Perspectives on Palcacocha lack truly cross-disciplinary research, missing more comprehensive insight. This contribution is unique for its analysis of diverse dimensions, which also provide a framework for other GLOF hazard, risk, and climate-related studies. The main aim of this contribution is to understand the links between them, their drivers and inhibitors.

Four dimensions were studied and linked at this stage: (i) the natural dimension; (ii) the human dimension; (iii) the legal dimension; and (iv) the ethical dimension. The natural (environmental) dimension thematically covers the lake's evolution and change of hazard over time, reflecting general post-LIA environmental change in the Cordillera Blanca. Exceptional growth of the lake was observed between 1970s ( $0.5 \cdot 10^6 \text{ m}^3$ ) and late 2000s ( $17.3 \cdot 10^6 \text{ m}^3$ ), undoubtedly linked to climate change-driven glacier retreat. The human dimension addresses the question of why people in Huaraz face continued and increasing vulnerability to GLOF despite longstanding efforts to reduce risk. This involves two principal aspects. First, the social and cultural dynamics that led certain populations to reject hazard zoning and subject themselves to GLOF risk. Second, shifting modes of governance from state-oriented development to neoliberalization, including levels of funding and resources for infrastructure and engineering projects.

While research on natural and human dimensions of GLOFs has a long tradition in the Cordillera Blanca, legal and ethical dimensions have come to the foreground in recent years. The legal dimension covers the question of broader responsibility for the in situ situation and the risk to property and people. Legally, only anthropogenic interference will be subject to attribution of responsibility. Discussion on this dimension is based on a law suit taken in Germany by a house owner in Huaraz trying to assign responsibility for damage aversion measures to an energy utility in Germany. It focuses on causation in a legal sense which is understood to be different from causation in a purely scientific sense. The ethical dimension covers two aspects. First, it concerns the question of who is responsible to subsidize measures to adapt to the GLOF risk but also the approaches to compensate for negative impacts after an outburst happened. Second, ethics aims to clarify who shall decide on the risks taken and the measures and approaches implemented. In so doing, the ethical dimension analyses what normative principles of justice would

be appropriate to decide on the distribution of burdens and how the choice of measures and approaches taken should be legitimized.