Lake evolution and glacial lake outburst floods (GLOFs) in deglaciating mountains

From regional insights to global contexts

Adam EMMER

Abstract: Glacial lake outburst floods (GLOFs) – sudden releases of water retained in glacial lakes – are among the consequences of retreating glaciers. In high mountain regions across the globe, glaciers have receded from their Little Ice Age (LIA) positions, leading to the formation and evolution of different types of glacial lakes. By integrating the analysis of remotely sensed imageries, documentary data sources, field data as well as other data and approaches, this study aims at revealing the relationship between evolution of different generations (and sub-types) of glacial lakes and the occurrence of GLOFs, and characterizing past events for better anticipation of future ones. The primary geographical focus of this work is on the Peruvian Andes with special attention given to the most glacierized part of it – the Cordillera Blanca, certain chapters and section also focus on High Asia (parts of Indian and Nepal Himalaya) and Austrian Alps (Tyrol and Salzburg provinces). This habilitation is designed as a collection of published studies of the author and the core of this work is a set of 23 peer-reviewed lake- and GLOF- oriented papers and one book chapter, published between 2015 and 2021.

Inventories of high mountain lakes prepared in this work provide insights into the characteristics and dynamics of evolution of glacial lakes in different parts of the world. Unlike most of the existing lake inventories, insights into qualitative lake characteristics (e.g. dam type, lake evolution phase) are derived and analyzed. Several thousands of lakes are inventoried in the three study regions (Peruvian Andes, Sikkim Himalaya, Austrian Alps), revealing general patterns suggesting that: (i) moraine-dammed lakes are dominant lake type forming and evolving in earlier stages of the post-LIA glacier retreat; (ii) the formation and evolution of bedrock-dammed lakes and lakes with combined dams dominate in later stages; (iii) relatively narrow elevational band hosts currently forming (proglacial) lakes. As a result of climate change-driven glacier retreat, this 'active' band of proglacial lakes evolution is documented to be shifting upwards and in combination with topographical setting control the formation and evolution of new glacial lakes.

This study presents unprecedently detailed GLOF inventory for the Peruvian Andes, which provides novel insights into the GLOF triggering and characterization and in combination with the lake inventory generate apparent utilizations for GLOF hazard identification and assessment efforts. It was shown that most of the high magnitude GLOFs originated from failures of moraine

dams of lakes in the proglacial stage of their evolution, highlighting the monitoring priority. Trigger-wise, rapid mass movements into the lake dominated, while other triggers were documented rather marginally. Strikingly, Peruvian Andes are among the few regions of the world where there is an evidence of earthquake triggering of GLOFs – a specific process chain. By combining GLOF inventory with the lake inventory, it is shown that GLOFs occur in temporal clusters (peak frequencies) which are associated with specific stages of glacier retreat, lake formation and evolution (e.g. an increased number of proglacial moraine-dammed lakes) or extreme triggering events (e.g. a strong earthquake). Importantly lagged response of glaciers, lakes and GLOFs to initial forcings are desired to be considered in the anticipation of future GLOFs.

A substantial part of this habilitation focuses on characterization and reconstruction of past GLOF events. Several recent (e.g. the 2020 Lake Salkantaycocha GLOF in Peru; the 2020 Lake Jinwuco GLOF in Tibet) as well as historic lake outbursts (e.g. the 1941 Lake Palcacocha GLOF) are analyzed and modelled in order to: (i) understand drivers and processes involved in GLOF preconditioning, triggering, propagation and attenuation; (ii) derive a set of plausible parameters for the modelling of potential future events. In addition, the evolution of future lakes and potential future GLOFs are modelled at selected study sites in Peruvian Andes and Indian Himalaya, with obvious implications for GLOF hazard and risk management.

Last but not least, observations and findings from study sites in South America, Asia and Europe are put into the context of GLOF research and sustainable development efforts in mountain regions across the globe.

Keywords: GLOFs, glacial lakes, Peruvian Andes, Cordillera Blanca, Sikkim Himalaya, Austrian Alps