Abstract of the thesis:

Outburst Floods in the Greater Himalayas - From Regional Susceptibility to Local Hazard

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High-mountain regions provide valuable ecosystem services, including food, water, and energy production, to more than 900 million people worldwide. Projections hold, that this population number will rapidly increase in the next decades, accompanied by a continued urbanisation of cities located in mountain valleys. One of the manifestations of this ongoing socio-economic change of mountain societies is a rise in settlement areas and transportation infrastructure while an increased power need fuels the construction of hydropower plants along rivers in the high-mountain regions of the world. However, physical processes governing the cryosphere of these regions are highly sensitive to changes in climate and a global warming will likely alter the conditions in the headwaters of high-mountain rivers. One of the potential implications of this change is an increase in frequency and magnitude of outburst floods – highly dynamic flows capable of carrying large amounts of water and sediments. Sudden outbursts from lakes formed behind natural dams are complex geomorphological processes and are often part of a hazard cascade. In contrast to other types of natural hazards in high-alpine areas, for example landslides or avalanches, outburst floods are highly infrequent. Therefore, observations and data, describing for example the mode of outburst or the hydraulic properties of the downstream propagating flow are very limited, which is a major challenge in contemporary (glacial) lake outburst flood research. Although glacial lake outburst floods (GLOFs) and landslide-dammed lake outburst floods (LLOFs) are rare, a number of documented events caused high fatality counts and damage. The highest documented losses due to outburst floods since the start of the 20th century were induced by only a few high-discharge events. Thus, outburst floods can be a significant hazard to downvalley communities and infrastructure in high-mountain regions worldwide.

This thesis focusses on the Greater Himalayan region, a vast mountain belt stretching across 0.89 million km^2. Although potentially hundreds of outburst floods have occurred there since the beginning of the 20th century, data on these events is still scarce. Projections of cryospheric change, including glacier-mass wastage and permafrost degradation, will likely result in an overall increase of the water volume stored in meltwater lakes as well as the destabilisation of mountain slopes in the Greater Himalayan region. Thus, the potential for outburst floods to affect the increasingly more densely populated valleys of this mountain belt is also likely to increase in the future. A prime example of one of these valleys is the Pokhara valley in Nepal, which is drained by the Seti Khola, a river crossing one of the steepest topographic gradients in the Himalayas. This valley is also home to Nepal's second largest, rapidly growing city, Pokhara, which currently has a population of more than half a million people – some of which live in informal settlements within the floodplain of the Seti Khola. Although there is ample evidence for past outburst floods along this river in recent and historic times, these events have hardly been quantified.

The main motivation of my thesis is to address the data scarcity on past and potential future outburst floods in the Greater Himalayan region, both at a regional and at a local scale. For the former, I compiled an inventory of >3,000 moraine-dammed lakes, of which about 1% had a documented sudden failure in the past four decades. I used this data to test, whether a number of predictors that have been widely applied in previous GLOF assessments are statistically relevant when estimating past GLOF susceptibility. For this, I set up four Bayesian multi-level logistic regression models, in which I explored the credibility of the predictors lake area, lake area dynamics, lake elevation, parent-glacier-mass balance, and monsoonality. By using a hierarchical approach consisting of two levels, this probabilistic framework also allowed for spatial variability on GLOF susceptibility across the vast study area, which until now had not been considered in studies of this scale. The model results suggest that in the Nyainqentanglha and Eastern Himalayas – regions with strong negative glacier-mass balances – lakes have been more prone to release GLOFs than in regions with less negative or even stable glacier-mass balances. Similarly, larger lakes in larger catchments had, on average, a higher probability to have had a GLOF in the past four decades. Yet, monsoonality, lake elevation, and lake area dynamics were more ambiguous. This challenges the credibility of a lake's rapid growth in surface area as an indicator of a pending outburst; a metric that has been applied to regional GLOF assessments worldwide.

At a local scale, my thesis aims to overcome data scarcity concerning the flow characteristics of the catastrophic May 2012 flood along the Seti Khola, which caused 72 fatalities, as well as potentially much larger predecessors, which deposited >1 km^3 of sediment in the Pokhara valley between the 12^{th} and 14^{th} century CE. To reconstruct peak discharges, flow depths, and flow velocities of the 2012 flood, I mapped the extents of flood sediments from RapidEye satellite imagery and used these as a proxy for inundation limits. To constrain the latter for the Mediaeval events, I utilised outcrops of slackwater deposits in the fills of tributary valleys. Using steady-state hydrodynamic modelling for a wide range of plausible scenarios, from meteorological (1,000 $m^3\ s^{-1}$) to cataclysmic outburst floods (600,000 $m^3\ s^{-1}$), I assessed the likely initial discharges of the recent and the Mediaeval floods based on the lowest mismatch between sedimentary evidence and simulated flood limits. One-dimensional HEC-RAS simulations suggest, that the 2012 flood most likely had a peak discharge of 3,700 $m^3\ s^{-1}$ in the upper Seti Khola and attenuated to 500 $m^3\ s^{-1}$ when arriving in Pokhara's suburbs some 15 km downstream.

Simulations of flow in two-dimensions with orders of magnitude higher peak-discharges in ANUGA show extensive backwater effects in the main tributary valleys. These backwater effects match the locations of slackwater deposits and, hence, attest for the flood character of Mediaeval sediment pulses. This thesis provides first quantitative proof for the hypothesis, that the latter were linked to earthquake-triggered outbursts of large former lakes in the headwaters of the Seti Khola – producing floods with peak discharges of >50,000 $m^3\ s^{-1}$.

Building on this improved understanding of past floods along the Seti Khola, my thesis continues with an analysis of the impacts of potential future outburst floods on land cover, including built-up areas and infrastructure mapped from high-resolution satellite and OpenStreetMap data. HEC-RAS simulations of ten flood scenarios, with peak discharges ranging from 1,000 to 10,000 $m^3\ s^{-1}$, show that the relative inundation hazard is highest in Pokhara's north-western suburbs. There, the potential effects of hydraulic ponding upstream of narrow gorges might locally sustain higher flow depths. Yet, along this reach, informal settlements and gravel mining activities are close to the active channel. By tracing the construction dynamics in two of these potentially affected informal settlements on multi-temporal RapidEye, PlanetScope, and Google Earth imagery, I found that exposure increased locally between three- to twentyfold in just over a decade (2008 to 2021).

In conclusion, this thesis provides new quantitative insights into the past controls on the susceptibility of glacial lakes to sudden outburst at a regional scale and the flow dynamics of propagating flood waves released by past events at a local scale, which can aid future hazard assessments on transient scales in the Greater Himalayan region. My subsequent exploration of the impacts of potential future outburst floods to exposed infrastructure and (informal) settlements might provide valuable inputs to anticipatory assessments of multiple risks in the Pokhara valley.