

## **Present and future runoff from a Central Himalayan watershed: the importance of monitoring strategies in the Langtang catchment and of the integration of ground data and remote sensing into a glacio-hydrological model**

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In high-elevation watersheds of the Himalayan region the correct representation of the internal states and process dynamics in glacio-hydrological models can often not be verified due to missing in-situ measurements. As a result, until recently simple models have been used to simulate the hydrology of high elevation catchments, often calibrated only against catchment runoff, an integrated variable of catchment response that can result in compensation of errors and equifinality issues.

The aim of this study is to provide a fundamental understanding of the hydrology of a Himalayan watershed through the systematic integration of a large amount of detailed and novel in-situ data into a physically-based, distributed glacio-hydrological model. The upper Langtang catchment in Nepal has been established since 2012 as a monitoring site thanks to joint effort from ICIMOD (the International Centre for Integrated Mountain Development), ETH Zurich, Utrecht University and other partners, and we show here the importance of this monitoring effort for improved simulations of glacier and runoff changes.

We make use of ground data from the catchment combined with high resolution satellite data to understand snow melt, glacier melt and mass balance, runoff generation and specific processes related to debris-covered glaciers that dominate in the catchment. We apply a new model for ablation under debris that takes into account the varying effect of debris thickness on melt rates. A novel approach is tested to reconstruct spatial fields of debris thickness through combination of energy balance modelling, UAV-derived geodetic mass balance and statistical techniques. Supraglacial lakes and cliffs are a prominent features of the debris-covered glaciers in the catchment and are indirectly taken into account by the model, and we show their importance for total glacier mass balance and runoff through detailed, physically-based modelling.

The systematic integration of in-situ data for model calibration enables the application of a state-of-the-art model with many parameters to model glacier evolution and catchment runoff in spite of the lack of continuous long-term historical records. It allows drawing conclusions on the importance of processes that have been suggested as being relevant in High Mountain Asia but never quantified before, such as the role of avalanches and melt from debris covered ice. The simulations show that during the hydrological year 2012/2013, 8.7% of total water inputs originated from glacier melt from debris covered area. Melt from snow that has been redistributed by avalanches is also an important contribution to runoff, and highly variable in space.

The model is then used to simulate the response of the catchment to a changing climate, using the downscaled output from the latest CMIP5 climate change scenarios. We show that climate warming leads to a decrease in glacier area and volume in the entire catchment, an increase in future icemelt and a peak in glacier runoff by mid-century. The increase in total icemelt is due to higher melt rates and large areas currently located above the equilibrium line altitude that will contribute to melt. Catchment runoff will not reach below current levels throughout the 21st century due to precipitation increases. Debris covered glacier area will disappear at a slower pace than non-debris covered area. We conclude by discussing the importance of the data collection effort on the accuracy of the present and future simulations, and suggest avenues of future research in monitoring and modelling.