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Hydrological modelling of alpine headwaters using centurial glacier evolution, snow and long-term discharge dynamics

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The response of alpine streamflows to long-term climate variations is highly relevant for the supply of water to adjacent lowlands. A key challenge in modelling high-elevation catchments is the complexity and spatial variability of processes, whereas data availability is rather often poor, restricting options for model calibration and validation. Glaciers represent a long-term storage component that changes over long time-scales and thus introduces additional calibration parameters into the modelling challenge. The presented study aimed to model daily streamflow as well as the contributions of ice and snow melt for all 49 of the River Rhine's glaciated headwater catchments over the long time-period from 1901 to 2006. To constrain the models we used multiple data sources and developed an adapted modelling framework based on an extended version of the HBV model that also includes a time-variable glacier change model and a conceptual representation of snow redistribution. In this study constraints were applied in several ways. A water balance approach was applied to correct precipitation input in order to avoid calibration of precipitation; glacier area change from maps and satellite products and information on snow depth and snow covered area were used for the calibration of each catchment model; and finally, specific seasonal and dynamic aspects of discharge were used for calibration. Additional data like glacier mass balances were used to evaluate the model in selected catchments. The modelling experiment showed that the long-term development of the coupled glacier and streamflow change was particularly important to constrain the model through an objective function incorporating three benchmarks of glacier retreat during the 20th Century. Modelling using only streamflow as calibration criteria had resulted in disproportionate under and over estimation of glacier retreat, even though the simulated and observed streamflow agreed well. Also, even short discharge time series from the first half of the 20th century considerably improved the calibration. For ungauged catchments some model parameters related to runoff were transferred from gauged catchments but re-calibration of snow and glacier parameters proved essential to constrain the simulations. This study clearly illustrates how essential long and short-term multiple data sources are to reduce parameter uncertainty which is commonly large in alpine environments. This study shows the particular benefit for long-term modelling in a changing climate.