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# Climate change impacts on future snow, ice and rain runoff in a Swiss mountain catchment using multi-dataset calibration

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A B S T R A C T

*Study region:* The hydropower reservoir of Gigerwald is located in the alpine valley Calfeisental in eastern Switzerland. The lake is fed by runoff from rain, snow melt and ice melt from a few small glaciers, as well as by water collected in a neighbouring valley.
*Study focus:* Water resources in the Alps are projected to undergo substantial changes in the coming decades. It is therefore essential to explore climate change impacts in catchments with hydropower facilities. We present a multi-dataset calibration (MDC) using discharge, snowcover data and glacier mass balances for an ensemble of hydrological simulations performed using the Hydrologiska Byråns Vattenbalansavdelning (HBV)-light model. The objective is to predict the future changes in hydrological processes in the catchment and to assess the benefits of a MDC compared to a traditional calibration to discharge only.
*New hydrological insights for the region:* We found that the annual runoff dynamics will undergo significant changes with more runoff in winter and less in summer by shifting parts of the summer melt runoff to an earlier peak in spring. We furthermore found that the MDC reduces the uncertainty in the projections of glacial runoff and leads to a different distribution of runoff throughout the year than if calibrated to discharge only. We therefore argue that MDC leads to more consistent model results by representing the runoff generation processes more realistically.

## 1. Introduction

The Earth's climate is changing. Global surface air temperature is projected to keep rising, while the amounts of snow and ice are declining in all assessed climate scenarios during the 21st century (IPCC, 2014). The impacts on global hydropower potential can hardly be generalized. However, for Europe a loss of about 6% in hydropower potential by 2070 compared to the average potential from 1961 to 1990 is projected (Lehner et al., 2005). It is likely to decrease in all sub-regions except for Scandinavia (Field et al., 2014). For Alpine catchments such as the Rhone basin (Beniston et al., 2014) and several others with hydropower stations (Swiss Society for Hydrology and Limnology (SGHL) and the Swiss Hydrological Comission (CHy), 2011) a slight trend towards decreasing annual runoff is predicted. In Switzerland around 56 % of the electricity production is covered by hydropower (SGHL and CHy, 2011) and is therefore highly dependent on the water availability throughout the year. High-alpine hydropower stations that are snow- and icemelt-dominated will be affected more severely by changing runoff regimes in the next decades (Hänggi et al., 2011; Addor et al.,

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2014). This is because a general trend of receding glaciers has been observed since the end of the 19th century according to long-term studies (Bauder et al., 2007; Paul et al., 2007; Zemp et al., 2015). Also the number of days with snowfall decreased from the 1980s until 1999, which is mainly visible at low to mid-elevations (Laternser and Schneebeli, 2003). The days of continuous snow cover as well as the amount of glacier ice acting as natural water reservoirs are projected to decline further or even disappear within the 21st century (CH2014, 2014; Huss et al., 2008). Catchments with a low degree of glacierization will switch from snow-dominated to rain-dominated altering the runoff seasonality towards more winter runoff and less summer runoff. However, the annual runoff is expected to remain at about the same level (CH2014, 2014; Zierl and Bugmann, 2005).

Therefore, annual runoff in glacier-dominated catchments is increasing to a certain maximum and then starts dropping as the glacier surfaces become smaller. The timing of the peak discharge depends on the catchment characteristics and location (Farinotti et al., 2012; Huss et al., 2008). For high-alpine hydropower stations the disappearance of the glacier ice in the long term will most probably lead to a decreasing productivity compared to today (Finger et al., 2012; SGHL and CHy, 2011). Finger et al. (2012) showed that up to one third of the production in the Vispa Valley might be lost due to declining glacier area, projected changes in precipitation and water loss due to inadequate water intakes of the existing hydropower infrastructure by 2100.

Studies for the timing and magnitudes of these discharge alterations can however not be generalized, as suggested by Gaudard et al. (2014) who found also increasing annual runoff sums in the Italian Part of the Alps. They hence have to be performed for every site individually. Nevertheless, possible changes in the seasonal distribution are vital for future water resource management. Even if the effects on the total annual runoff seem to be small, they will have an effect on the water availability for energy production throughout the year. These regime alterations ask for well-balanced management of runoff from Alpine catchments (CH2014, 2014).

Most studies that aim at predicting impacts of climate change use a calibrated hydrological model driven with data of future climate scenarios for projecting discharge until the year 2100. However, the approaches differ in their methodology, the input data and also in their complexity. In recent years the quantile mapping approach developed by Panofsky and Brier (1968) has been increasingly used to correct for systematic biases in climate model outputs, in particular biases in the mean and variability (Teutschbein and Seibert, 2012; Themessl et al., 2011). It has become a standard technique for climate change impact-studies in hydrology (Finger et al., 2012; Ravazzani et al., 2016; Vormoor et al., 2015).

Since the beginning of hydrological modelling research in the 1970s, model calibration focused on fitting simulations to observed discharge data (Boughton, 1966; Johnston and Pilgrim, 1976; Lichty et al., 1968). This practice has also been used in more recent works investigating climate change impacts on water resources in glaciated areas (Köplin et al., 2013; Schaefli et al., 2007). Since the 1990s, several modelling studies in different fields used additional datasets besides runoff to calibrate hydrological models. Examples are groundwater and soil moisture data (Motovilov et al., 1999), soil saturation (Franks et al., 1998) or stream salinity data (Kuczera and Mroczkowski, 1998). In mountainous regions glacier mass balances and remotely-sensed snow cover proved to be valuable sources of information (Frans et al., 2015; Koboltschnig et al., 2008; Paul et al., 2009). For strongly glacierized catchments, several studies indicated that an accurate modelling of glacier mass balances is crucial (Huss et al., 2008; Magnusson et al., 2010; Stahl et al., 2008). In a catchment with a very low degree of glacierization, however, the role of snow cover becomes more important since it is highly sensitive to changes in temperature as shown by analysing time series of snow records on the West Coast of the United States from 1960 to 2002 (Mote, 2006) as well as by modelling studies in Switzerland (Bavay et al., 2013), Finland (Rasmus et al., 2004) and on a global scale (Barnett et al., 2005). Especially at lower elevations, the snow cover is particularly sensitive to temperature changes (Hantel and Hirtl-Wielke, 2007; Laternser and Schneebeli, 2003). This is one of the main reasons for its important influence on runoff dynamics (Bavay et al., 2013, 2009; Finger et al., 2015; Horton et al., 2006). Finger et al. (2015) showed that if glacier mass balances or snow cover are disregarded in the calibration phase, the model may simulate runoff accurately but for the wrong reasons (Kirchner, 2006) and, hence, lead to a misinterpretation of the components of runoff (rain fall, snow melt, glacier melt). Thus, model results are more likely to be "right for the right reasons" if additional datasets are used for constraining the model. This is particularly important if the model calibration is subsequently used for climate predictions (Finger et al., 2015). The methodology of calibration using multiple datasets and also using quantile mapped climate scenarios has only been applied using the physically based TOPKAPI model (Finger et al., 2012). With a transfer of the methodology to a conceptual model, such as the Hydrologiska Byråns Vattenbalansavdelning (HBV)-light model (Seibert and Vis, 2012) the calculations could be done more efficiently permitting to explore the entire parameter space.

The objectives of this paper are (i) to demonstrate that the multi-dataset calibration (MDC) leads to more realistic hydrological simulations under present climate, and hence, to more reliable projected changes, than a calibration based on discharge alone $Q_{only}$; (ii) to quantify the contribution of the different components of the model chain to the uncertainty in projected discharge using an analysis of variance (ANOVA); and (iii) to assess the impacts of climate change on glaciers, snow and runoff in the catchment of the Gigerwaldsee with the MDC in comparison to $Q_{only}$. These objectives provide the structural sub-headings used in the Methods, Results and Discussions sections, namely: (i) Multi-Dataset Calibration, (ii) ANOVA, and (iii) Discharge Scenarios.

## 2. Study site and data

### 2.1. Study site

The Gigerwaldsee lies in eastern Switzerland, about 80 km southeast of Zurich (see Fig. 1). The lake has a usable volume of $33.4 \times 10^6$ m$^3$ and a surface area of 0.71 km$^2$. It is fed by its natural catchment, the Calfeisental (52 km$^2$) and also by eight partial catchments with a total area of 45 km$^2$, where water is collected from the Weisstannental (see numbers 1–7 in Fig. 1) in the North and the small Tersoltal (8) in the East of the Calfeisental. Electricity is generated in the power plant Mapragg the compensating reservoir

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