The compensating effect of glaciers: Characterizing the relation between interannual streamflow variability and glacier cover

Marit van Tiel\(^1\) | Irene Kohn\(^1\) | Anne F. Van Loon\(^2\) | Kerstin Stahl\(^1\)

\(^1\)Environmental Hydrological Systems, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany
\(^2\)School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

Correspondence
Marit van Tiel, Environmental Hydrological Systems, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany.
Email: marit.van.tiel@hydrology.uni-freiburg.de

Abstract
Meltwater from glaciers is not only a stable source of water but also affects downstream streamflow dynamics. One of these dynamics is the interannual variability of streamflow. Glaciers can moderate streamflow variability because the runoff in the glacierized part, driven by temperature, correlates negatively with the runoff in the non-glacierized part of a catchment, driven by precipitation, thereby counter-balancing each other. This is also called the glacier compensation effect (GCE), and the effect is assumed to depend on relative glacier cover. Previous studies found a convex relationship between streamflow variability and glacier cover of different glacierized catchments, with lowest streamflow variability at a certain optimum glacier cover. In this study, we aim to revisit these previously found curves to find out if a universal relationship between interannual streamflow variability and glacier cover of different glacierized catchments, with lowest streamflow variability at a certain optimum glacier cover, exists, which could potentially be used in a space-for-time substitution analysis. Moreover, we test the hypothesis that the dominant climate drivers (here precipitation and temperature) switch around the suggested optimum of the curve. First, a set of virtual nested catchments, with the same absolute glacier area but varying non-glacierized area, were modelled to isolate the effect of glacier cover on streamflow variability. The modelled relationship was then compared with a multicatchment data set of gauged glacierized catchments in the European Alps. In the third step, changes of the GCE curve over time were analysed. Model results showed a convex relationship and the optimum in the simulated curve aligned with a switch in the dominant climate driver. However, the multicatchment data and the time change analyses did not suggest the existence of a universal convex relationship. Overall, we conclude that GCE is complex due to entangled controls and changes over time in glacierized catchments. Therefore, care should be taken to use a GCE curve for estimating and/or predicting interannual streamflow variability in glacierized catchments.

KEYWORDS
glacier compensation effect, glacierized catchments, interannual variability, modelling experiment, space-for-time substitution, streamflow

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Streamflow variability is related to climate variability, for instance heat waves, seasonality of precipitation and temperature, and climate modes (e.g., Barlow, Nigam, & Berbery, 2001; Dettinger & Díaz, 2000), and moderated by catchment storages, such as lakes, groundwater, and soil characteristics (e.g., Andrés Doménech, García Bartual, Montanari, Segura, & Bautista, 2015; Milly & Wetherald, 2002). In mountain regions, snow and particularly glaciers represent such storages that can modify the streamflow response to climate input (e.g., Collins, 2006a; Dahlke, Lyon, Stedinger, Rosqvist, & Jansson, 2012; Fleming & Dahlke, 2014; Jansson, Hock, & Schneider, 2003; Jenicek, Seibert, Zappa, Staudinger, & Jonas, 2016; Viviroli et al., 2011). Many timescales of variability exist, for example daily variations, intra-annual and interannual variability, and decadal variability. In mountain regions, interannual variability of streamflow is particularly important because it characterizes the reliability of water supply for diverse water uses, for example, hydropower (Schaefli, Manso, Fischer, Huss, & Farinotti, 2019). The interannual streamflow variability of glacierized catchments will therefore be the focus of this study.

In mountain regions, glaciers can decrease the streamflow variability in partly glacierized catchments because the glacierized part of the catchment has an opposite runoff regime compared with the non-glacierized part of the catchment, thereby counterbalancing each other (Braithwaite & Olesen, 1988; Meier & Tangborn, 1961; Rothlisberger & Lang, 1987). The non-glacierized part is characterized by a rainfall-runoff regime and the glacierized part by a melt-dominated regime. This means that, in a catchment where both of these runoff regimes are present, during warm and dry periods, the melt from the glacierized part could compensate for the lack of precipitation in the non-glacierized part (e.g., Koboltschin, Schönér, Holzmann, & Zappa, 2009; Zappa & Kan, 2007). On the other hand, during cold and wet periods, runoff from the non-glacierized part could compensate for the lack of melt from the glacierized part (e.g., Hopkinson & Young, 1998). This process is called the glacier compensation effect (GCE, e.g., Fountain & Tangborn, 1985; Rothlisberger & Lang, 1987).

How much the two different hydrological regimes in a glacierized catchment can counterbalance each other is considered to depend on the relative area of the glacierized part and the non-glacierized part (e.g., Fountain & Tangborn, 1985), that is, the catchment’s glacier cover fraction (g). If the non-glacierized part covers a large part of the catchment, precipitation variability will mainly control streamflow variability. If on the other hand the glacier covers a large part of the catchment, streamflow variability is dominated by temperature variability (e.g., Casassa, López, Pouyaud, & Escobar, 2009; Collins, 2006a; Rothlisberger & Lang, 1987). Several empirical studies looked at the relation between g and streamflow variability, expressed as the coefficient of variation (CVQ) for different samples of catchments (Braithwaite & Olesen, 1988; Chen & Ohmura, 1990; Collins, 2006b; Fleming & Clarke, 2005; Fountain & Tangborn, 1985; Krimmel & Tangborn, 1974; Meier & Tangborn, 1961; Moore, 1992), and some of them found a convex nonlinear relationship with higher CVQ at low and high g (Chen & Ohmura, 1990; Fountain & Tangborn, 1985). This convex relationship (see conceptual curve in Figure 1) was found to have an optimum (minimum CVQ, maximum compensation, GCEopt) at ~36% g for a U.S. data set (Fountain & Tangborn, 1985) and at ~39–44% g for a data set in the European Alps (Chen & Ohmura, 1990). Most of the other studies only looked at a small sample of glacierized catchments and were therefore only able to confirm parts of the relationship. Moreover, Moore (1992) and Collins (2006b) discuss that finding a relation between g and CVQ can be complicated because other factors than just g, for example, elevation range, glacier hypsometry, climate characteristics, and snow on the glacier, influence the interplay between runoff from the glacierized part (Qgl) and the non-glacierized part (Qnongl).

Despite these few empirical studies that suggest a nonlinear convex relationship between g and CVQ, later research has not built on these studies to establish a universal relationship for the influence of glaciers on streamflow variability. However, some studies used the relationships found to estimate and/or compare CVQ (e.g., Hopkinson & Young, 1998). Also, research into the processes’ relative importance underlying the hypothesized curve has been limited. This is in stark contrast to the many studies that mention the compensation effect of glaciers as general motivation for why it is important to study the role of glaciers in hydrology. If a universal relationship could be found, it would help to better understand spatial differences in flow reliability. This would have a number of advantages for water resources planning such as decisions on where to install small hydropower plants or intakes for water supply (Gaudard et al., 2014; Schaeffli et al., 2019).

Also, if a universal relationship between g and CVQ existed, it could be used to estimate how CVQ of a specific catchment would change over time due to deglaciation (following the GCE curve from right to left), which is crucial information for water management and planning. The intraregional comparison of catchments’ CVQ and g in previous studies might thus be interpreted as a space-for-time substitution (Singh, Wagener, Werkhoven, Mann, & Crane, 2011). This
translation, going from a relationship based on different catchments to a relationship for one catchment over time, has recently been applied for the Budyko curve (Carmona, Sivapalan, Yaeger, & Poveda, 2014; Sivapalan, Yaeger, Harman, Xu, & Troch, 2011). Hock, Jansson, and Braun (2005) already interpreted the GCE curve as a space-for-time substitution. They hypothesized that under global warming, the

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increase (decrease) and increase later on. However, we argue that before any time interpretations of the curve are made, a more systematic analysis of the compensation effect and the relationship between $g$ and $CV_Q$ is needed.

The GCE curve, as sketched in Figure 1, could be interpreted in three ways:

1. several nested catchments with the same absolute glacier area but
   different $g$ due to larger/smaller non-glacierized area (with outlet
   further downstream/upstream);
2. different catchments within a specific region (e.g., Chen & Ohmura,
   1990); and
3. one catchment with changing $g$ over time due to deglaciation
   (e.g., hypothesized by Hock et al., 2005).

A data set of the first type has not been used to define or corroborate a GCE curve yet, most likely because there is no appropriate streamflow data set available from several nested undisturbed catchments with the same absolute glacier area covering a $g$ range large enough to fit or test a relationship. Neither has an examination of the climate drivers of streamflow variability in relation to the GCE curve been carried out. We hypothesize that precipitation is the dominant driver of streamflow variability below $GCE_{opt}$ and temperature is the dominant driver above $GCE_{opt}$. So, catchments to the right of the optimum would have a higher correlation of streamflow with temperature ($r_{T-Q}$) than with precipitation ($r_{P-Q}$) and vice versa for catchments to the left of the optimum (Figure 1). If data can confirm this hypothesis, then the correlation of streamflow with temperature and precipitation might be an indicator of the catchments’ location relative to the optimum.

In this study, we test the different interpretations of the GCE curve and its climate controls with the aim of challenging the existence of a universal (convex) relationship between streamflow variability and glacier cover. This will give a better insight in whether the relationship can be used for planning and predictions of future water reliability in glacierized catchments under climate change. By a universal relationship we mean that, for a certain region, a convex relationship can be fitted through some data points and that other catchments, as well as a particular catchment during deglaciation, in this region follow(s) this curve.

The study is organized as follows: First, we perform a model experiment with virtual nested catchments (Interpretation 1 as mentioned above) to isolate the effect of $g$ on $CV_Q$, to look at the streamflow components $Q_g$ and $Q_{nongl}$, and to investigate the climate drivers. Next, the modelled relationship is compared with observation data of catchments in the Swiss and Austrian Alps (Interpretation 2) to examine whether such a GCE relationship can be found for the region of the Alps and to confirm or reject, with more recent data, the previously found relationship for the Alps (from Chen & Ohmura, 1990). In addition to the $g$-$CV_Q$ relationship, correlations with climate drivers are analysed. Last, we explore the time aspect of the relationship (Interpretation 3). We evaluate the $g$-$CV_Q$ relationship in different periods and analyse changes of $CV_Q$ over time for a selection of long streamflow records.

## 2 DATA AND METHODS

### 2.1 Model experiment

As a first step in analysing the relationship between $CV_Q$ and $g$, a model experiment was carried out (e.g., Rees & Collins, 2006). A virtual nested catchment model framework enabled the analysis of the compensating effect in a controlled way. Nested catchments form a natural laboratory to analyse the influence of differences in $g$ while most other factors are similar. Specifically, we aim to test if realizing this nested catchment approach by hydrological modelling results in a convex relationship as hypothesized.

The setup of our virtual nested model catchments is based on a real catchment, using observed glacier geometries and area elevation distributions (Figure 2). The catchment taken as starting point is the Schwarze Lütchine, located on the north side of the Swiss Alps. The glacier outline for the year 1973 and a digital elevation model were used to define the glacierized area and elevation zones with a 100-m interval. $g$ in the original catchment, comprising subcatchments 1–4, is 20.1% (36.1 km²). To design model catchments with $0% < g < 100%$, we decreased (increased) the non-glacierized area of the original catchment to increase (decrease) $g$. In this way, we vary $g$, but keep glacier geometry constant and climate input comparable between the different nested model catchments.

Increasing $g$ was done by removing the subcatchments (Table 1, Figure 2), one after the other, thereby reducing the original catchment area. Adding additional non-glacierized area to the original catchment required a virtual approach because the outlet in the real setting cannot be moved further downstream (another glacierized tributary joining and the river ending in Lake Brienz). Therefore, a clone of subcatchment 1 was added as many times as was needed to create a model catchment with $g$ of 15%, 10%, 5%, 3%, and 1% (Table 1). For the lowest $g$ (0%) model catchment, we took the virtual catchment $g_1$ (Table 1), and changed the glacier area in this catchment into non-glacierized area. For $g_{100}$, the catchment area corresponded to the glacier area.

The HBV-light software (Seibert & Vis, 2012; Seibert, Vis, Kohn, Weiler, & Stahl, 2018) was used to model the streamflow of these nested glacierized catchments. HBV-light is a semidistributed model based on hydrological response units defined by elevation zones, aspect classes, and glacierized/non-glacierized areas. The model has different routines: snow and glacier, soil, response, and routing. The melt in the snow and glacier routine is calculated with a degree-day method and a higher degree-day factor is used for glacier ice
compared with snow. The model simulates discharge in daily time-steps (Q) and also calculates the streamflow originating from the glacierized (Q_{gl}) and the non-glacierized part (Q_{nongl}) of the catchments, so that

\[ Q = Q_{gl} + Q_{nongl} \]

whereby Q_{gl} includes streamflow from rain, snowmelt, and ice melt, and Q_{nongl} includes streamflow from rain and snow melt. For a detailed model description, we refer to Seibert and Vis (2012) and Seibert et al. (2018).

The model settings are based on Stahl et al. (2017) and Meyer et al. (2019), who modelled the original catchment as one of the headwater catchments of the river Rhine. Catchment model settings (elevation zones, aspect classes, and glacierized and non-glacierized area fractions) were calculated for each of the nested model catchments. The model for each of the nested catchments was forced with the same daily temperature (T) and precipitation (P) data (representative for the mean elevation of the original catchment) from Meteoswiss (RhiresD and TabsD gridded products, MeteoSwiss, 2013, 2016), with T and P corrected for elevation according to a gradient. Mean annual precipitation sums range from 1,456 mm for the lowest to 2,211 mm.

TABLE 1  The nested model catchments with different relative glacier covers

| Model catchments | Glacier cover | Subcatchments included | Clone(s) of subcatchment 1 added | Mean elevation (m a.s.l.) |
|------------------|---------------|------------------------|----------------------------------|--------------------------|
| Original         |               |                        |                                  |                          |
| \$g_{orig}$      | 20.1%         | 1, 2, 3, 4             | 0                                | 2058                     |
| Decreased glacier cover |
| \$g_{15}$       | 15.2%         | 1, 2, 3, 4             | 2                                | 1908                     |
| \$g_{10}$       | 10.2%         | 1, 2, 3, 4             | 6                                | 1756                     |
| \$g_{5}$        | 5.1%          | 1, 2, 3, 4             | 18                               | 1603                     |
| \$g_{3}$        | 3%            | 1, 2, 3, 4             | 35                               | 1539                     |
| \$g_{1}$        | 1%            | 1, 2, 3, 4             | 117                              | 1478                     |
| Increased glacier cover |
| \$g_{24}$       | 24%           | 2, 3, 4                | 0                                | 2176                     |
| \$g_{37}$       | 37.2%         | 3, 4                   | 0                                | 2413                     |
| \$g_{57}$       | 57.2%         | 4                      | 0                                | 2703                     |
| Extreme glacier covers |
| \$g_{0}$        | 0%            | 1, 2, 3, 4             | 117                              | 1478                     |
| \$g_{100}$      | 100%          | Part of 4              | 0                                | 2819                     |

FIGURE 2  Base catchment used to create the virtual catchments for the model experiment. Numbers indicate the different subcatchments.
for the highest catchment. Parameters were taken from Meyer et al. (2019), who calibrated the model on multiple criteria, including streamflow data, estimated glacier volumes, and on a gridded snow water equivalent product from SLF (Swiss WSL-institute for Snow and Avalanche Research). Streamflow was modelled for the period 1976–2015, and the glacier area was kept constant during the simulation of this period for each modelled catchment.

2.2 Multi-catchment data set

The relationship between CVQ and $g$ from the modelled nested catchments was compared with the relationship obtained from streamflow observations of 39 gauged catchments in the Swiss and Austrian Alps (Table A1, Figure 3). All catchments are situated at approximately the same latitude, but they are distributed from west to east over the Alps. Their $g$ range from 0% to 73.5%, based on outlines for the year 2010 and 2012 for Switzerland and Austria, respectively (Table 2). For reference, the data set also contains four Swiss non-glacierized catchments.

Most catchment areas are between 10 and 100 km² with some larger ones between 200 and 517 km². The mean elevation is around 2,000–2,500 m a.s.l. for the glacierned and around 1,000–1,500 m a.s.l. for the non-glacierized catchments. The highest catchment (3,122 m a.s.l. mean elevation) is the Vernagtbach catchment in Austria, which also has the highest glacier cover and is one of the smallest catchments. In a few catchments, the elevation range is more than 2,500 m (see Table A1). Glacier area ranges from smaller than 1 km² to larger than 100 km².

Mean annual precipitation sums in the catchments range from 940 mm to more than 2,300 mm. Precipitation is highest in summer for all catchments, with a second smaller peak around November. Monthly mean temperatures are in general above 0°C between May and October for the glacierned catchments and only below 0°C in winter (December–February) for the non-glacierned catchments. Mean annual temperatures are higher for the non-glacierned catchments because of their lower elevation. Daily P and T data are taken from interpolated observations: the SPARTACUS gridded product (1 × 1 km, Hiebl & Frei, 2016, 2018) for Austria and the RhiresD (~1×1 km, precipitation) and TabsD (~1×1 km, temperature) gridded products (MeteoSwiss, 2013, 2016) for Switzerland.

All streamflow records have a length of at least 40 years (one selection criterion for catchments was that streamflow time series cover the period 1976–2015). Some of the Swiss catchments have streamflow records starting already before 1950. Daily streamflow data were obtained from the FOEN (Swiss Federal Office for the Environment) and from the eHYD database from the Austrian Federal Ministry Sustainability and Tourism (https://ehyd.gv.at/). Daily data for the Vernagtbach (Austria) were available for summer (May–October) days only and winter data were infilled with the same mean monthly data every winter from Escher-Vetter, Braun, and Siebers

![FIGURE 3 Location of the study catchments in Switzerland and Austria. The arrow shows the location of the catchment that was used as basis for the model experiment. This catchment was not part of the multicatchment analysis](image)

| TABLE 2 | Glacier outline data sets and their references for Switzerland and Austria |
|---------|---------------|---------------|---------------|
| Switzerland | Austria |
| $g$ inventory year | Reference | $g$ inventory year | Reference |
| 1935 | Freudiger, Mennekes, Seibert, & Weiler, 2018 | 1969, 2006 | Fischer, Seiser, Stocker-Waldhuber, Mitterer, & Abermann, 2015 |
| 1973 | Müller, Caflish, & Müller, 1977; Maisch, Wipf, Denneler, Battaglia, & Benz, 2000 | 2012 | CORINE land cover data |
| 2003 | Paul, Frey, & Le Bris, 2011 | | |
| 2010 | Fischer, Huss, Barboux, & Hoelzle, 2014 | | |
(2014) who found a low winter variability based on a few stage measurement campaigns (Escher-Vetter & Siebers, 2014). Two records had gaps of two and three years of data, respectively (in the period 1976–2015). These years were excluded from the analysis for these catchments. All streamflow records are assumed to be undisturbed. However, two catchments are flagged by the FOEN as influenced (e.g., by subdaily hydropoaking; see Table A1). As no typical hydropoaking signal or other disturbance signal was evident in the daily streamflow time series, we assumed that the influence is negligible with the monthly and annual time resolutions used in this study.

2.3 | Analysis of streamflow variability

The coefficient of variation (CV)

\[
CV_Q = \frac{\sigma}{\mu}
\]

was used as metric for interannual streamflow variability (Chen & Ohmura, 1990; Fountain & Tangborn, 1985). CVQ was calculated for yearly values of annual streamflow (Qann) and August streamflow (Qaug). August was selected because it can be assumed to be the month with highest ice melt because seasonal snow has melted from the glacier surface (Jost, Moore, Menounos, & Wheate, 2012; Lang, 1973; Stahl & Moore, 2006), although some studies also found September to be the month with highest glacier melt contribution (e.g., Frans, Istanbulluoglu, Lettenmaier, Fountain, & Riedel, 2018). CVQ was plotted against g to test for the presence of a GCE curve (Figure 1). Leap days were removed before aggregating daily streamflow series. Only streamflow sums from years or months without any data gaps were considered. CVQ was calculated for the period 1976–2015 both for the model experiment and the multicatchment data set.

To analyse the potential controls on the GCE curve (see Introduction) and GCEopt, we examined how streamflow variability relates to precipitation and temperature variability, by calculating the Spearman correlation coefficient between streamflow and the two climate variables (rP–Q, rT–Q). Correlation coefficients were calculated for all catchments from the model experiment and the multi-catchment data set for the same period as CVQ (1976–2015).

2.4 | Time stability of GCE curve

For some of the Swiss catchments in the multi-catchment data set, long time series are available (>40 years). For a selection of those, CVQ was calculated for different subperiods (see Table A1). The definition of the subperiods was based on the reference years of available g data. We used the glacier outline data sets of 1935, 1973, and 2003 (Table 2). The corresponding 20-year subperiods to derive CVQ were 1932–1951, 1965–1984, and 1996–2015. Plotting, for each catchment, the CVQ of the subperiods against the g of the subperiods shows whether changes in g over time lead to expected changes in CVQ (following the curve, decreasing, or increasing CVQ).

Furthermore, we also tested how stable the relationship is in time by calculating CVQ for two 20-year periods (1965–1984 and 1996–2015 for the multi-catchment data set, 1976–1995 and 1996–2015 for the model experiment) and relating them to the g values from the available glacier inventories in 1969 and 2006 for Austria and 1973 and 2003 for Switzerland. Then, a second-order polynomial was fitted, as suggested by Chen and Ohmura (1990), and compared for the two periods. Also here, the three to five gap years in three of the catchments in the different analyses periods were excluded from the analyses.

3 | RESULTS

3.1 | Model experiment

The CVQ values of the virtual nested catchments show a convex relationship with g (Figure 4a,b). The GCE curve optimum lies around g = 15% for Qann, and around g = 10% for Qaug. CVQ is generally higher for Qaug than for Qann, especially at high and low g. The CVQ of the g100 catchment shows some deviation from a smooth curve. The correlation of streamflow with precipitation and temperature cross at g 15–20% for Qann, and at g 10–15% for Qaug, which corresponds with the optimum in the GCE curve (Figure 4c,d). As expected, streamflow of catchments with high g correlates more strongly with temperature than with precipitation, for the low g catchments it is opposite. With increasing g, the increase/decrease of the correlations levels off. The anomalies of the two streamflow components Qgl and Qnongl (standard deviation shown in Figure 4e,f) are of the same magnitude around GCEopt. The 1:1 ratio of the two streamflow components is found between g 24% and 37.2% for Qann and at g = 15% for Qaug (Figure 4g,h). Although the magnitude of the component and the magnitude of the component anomaly are related, they show a 1:1 ratio at different g. The ratios show higher values for Qaug, indicating that compared with the whole year, Qgl is a more important contributor to total streamflow in August.

Figure 5 illustrates the compensating effect by showing the anomalies of the streamflow components Qgl and Qnongl per year. In catchments with g lower than the optimum (g10 and g30, Figure 5, left column), the Qnongl anomalies are larger than the Qgl anomalies. A negative anomaly in Qnongl, for example, due to a precipitation deficit, cannot be offset by a positive anomaly in Qgl because Qgl is not large enough. On the other hand, for catchments with g above the optimum (g57 and g82, Figure 5, right column), the Qgl anomalies are much larger than those of Qnongl, and, therefore, they can also not counterbalance each other. At g near the GCE curve optimum (g15 and g10, Figure 5, middle column), the Qg and Qnongl anomalies are similar. Besides being of comparable magnitude, the direction of the anomalies should also be opposite to counterbalance each other. In most years, this is the case (e.g., 1977, 1978), but sometimes the anomalies have the same sign (e.g., 1996 for Qanno). Total streamflow (Figure 5) shows the effect of the interplay of the two components. For example, at low g, Qanno and Qaug are mostly determined by anomalies in Qnongl, but in...
years when $Q_{gl}$ is more substantial and opposite to $Q_{nongl}$, total streamflow is closer to the mean streamflow. Near GCE\textsubscript{opt}, total streamflow shows large deviations when the anomalies have the same sign and close to average values when the anomalies are opposite.

### 3.2 Multi-catchment empirical analysis

Figure 6 shows the same type of analysis as in Figure 4a–d, but now for the observed streamflow records from the multicatchment data set instead of the modelled nested catchments. In general, the CVQ of observed streamflow is higher than the modelled CVQ (dashed line). The CVQ of the multicatchment data set shows a scatter, and it is difficult to find a clear curve with an optimum. For $Q_{ann}$, CVQ decreases with increasing $g$ between 0% and 15%. This part of the graph is, however, dominated by the four non-glacierized catchments showing high CVQ (Figure 6a,b). There are not many catchments with a high $g$. The Vernagtbach catchment (with highest $g$, 73.5%) is an important data point to indicate a potential increase in CVQ, going from moderate to high $g$, especially for $Q_{ann}$. However, its data are uncertain for $Q_{ann}$ due to the infilling of mean winter streamflow values. For both $Q_{ann}$ and $Q_{aug}$...
the Vernagtbach catchment shows a much higher CVQ compared with the model experiment. For Qaug, the decrease and subsequent increase in CVQ from non- to high-glacierized catchments is more evident than for Qann, but the scatter near the modelled optimum is large. The correlations of streamflow with precipitation and temperature, rP-Q and rT-Q, are more comparable to the model results.
The crossing of the correlations is present, although again, there is a scatter. The observations show a range of \( g \) where \( r_{P-Q} \) and \( r_{T-Q} \) have approximately the same value rather than one crossover point. This range is narrower for \( Q_{\text{aug}} \) than for \( Q_{\text{ann}} \). The few catchments with \( g < 1\% \) show a larger range of correlation values than those modelled for the two nested catchments with lowest \( g, g_0 \), and \( g_1 \).

3.3 | Changes of streamflow variability over time

Another test of the GCE curve theory is to see if \( CV_Q \) changes over time follow the expected curve pattern. Few series are long enough to study changes in time, and in those catchments, \( g \) changes over time (x-axis) are rather small and none of the changes represent a large part of the entire GCE curve (Figure 7), although \( g \) is decreasing over time for all catchments. The \( CV_Q \) of \( Q_{\text{ann}} \) of the 20-year periods for the selected catchments are closer to the GCE curve from the model experiment than the \( CV_Q \) values resulting from the 40-year analysis for the complete multicatchment data set (Figure 6a), which were distinctly higher. Most of the changes over time for \( Q_{\text{ann}} \) broadly follow the shape of the curve in terms of decreasing/increasing \( CV_Q \), apart from the catchment with lowest \( g \). For \( Q_{\text{aug}} \), the two highest glacierized catchments also show different patterns (Figure 7). However, the different catchments cannot be connected by an ideal curve because they have very different \( CV_Q \) or different rates of change of \( CV_Q \) (different slopes). The catchment closest to the modelled GCEopt (black line in Figure 7) shows a reversed pattern of the GCE curve because instead of decreasing and then increasing \( CV_Q \) when passing the optimum \( g \), the data shows increasing and then decreasing \( CV_Q \). Most of the catchments show a different trend in \( CV_Q \) for \( Q_{\text{ann}} \) compared with \( Q_{\text{aug}} \).

Using a larger subsample of the multicatchment data set and fitting a second-order polynomial through the data points, as done by Chen and Ohmura (1990), result in very different curves for different time periods (Figure 8, left). The curve for the later period, 1996–2015, agrees most with the curve from Chen and Ohmura (1990), although in their study data from years until 1985 were used. Moreover, especially the earlier period, 1965–1984, shows that a second-order polynomial might not be the best function to describe the relation between \( CV_Q \) and \( g \). Also in the model experiment, the fitted curves differ between the two periods (Figure 8b). The later period, 1996–2015, shows lower \( CV_Q \) for the moderate- to high-glacierized catchments compared with the earlier period, 1976–2015.

4 | DISCUSSION

4.1 | Is there a universal relationship between glacier cover and interannual streamflow variability?

The model experiment confirmed the hypothesis of a convex relationship between \( g \) and \( CV_Q \) (Figure 4). In a controlled nested catchment setting, glacier cover thus influences streamflow variability. The left part of the curve (where rainfall–runoff regimes are dominant) was steeper than the right part (where melt regimes are dominant), more so for August streamflow. This suggests that precipitation and temperature may influence the streamflow variability differently and is broadly consistent with the asymmetric behaviour found for correlations of streamflow with precipitation and temperature. Results of this model experiment, however, do not support the simple quadratic shape of the GCE curve suggested by Chen and Ohmura (1990) for the Alps. The multicatchment data set had overall higher \( CV_Q \) than the modelled virtual catchments; the modelled GCE curve appears to represent a lower envelope of the multicatchment \( CV_Q \). This is possibly due to the general tendency of underestimation of streamflow variability, including extremes, by a model (e.g., Whitfield, Wang, & Cannon, 2003) and due to our idealized nested catchment model framework in which, for example, parameters do not change with

![Figure 7](https://via.placeholder.com/150)

**Figure 7** CVQ of Qann (left) and Qaug (right) for three 20-year time windows around glacier cover inventory dates (different symbols) for eight Swiss catchments (different colours) with long observed streamflow time series. The dashed grey curve in the background is from the model experiment as shown in Figure 4a and b.
catchment size, glaciers are modelled statically, and other simplifications. The scatter was high and the multicatchment data set did only roughly show a GCE curve (Figure 6). Decreasing streamflow variability with increasing \( g \) in the low-glacierized part was evident for \( Q_{\text{ann}} \) and \( Q_{\text{aug}} \). At the GCE\(_{\text{opt}} \) of the model experiment for \( Q_{\text{aug}} \), the multicatchment data set showed a large range of CVQ. An increase in CVQ to the right of an assumed optimum was less evident and depended strongly on one data point for the catchment with the highest glacier cover (73.5% Vernagtbach), which has infilled streamflow data in winter due to discontinuous streamflow monitoring.

In the multicatchment data set and the model experiment, the correlations with climate drivers showed a crossover. From low- to high-glacierized catchments, the correlation of streamflow with precipitation decreased, whereas the correlation with temperature increased. However, only in the model experiments, due to the clear GCE curve, the crossover of correlations could be clearly related to the optimum in the GCE curve. In the multicatchment data set, a similar correlation in \( r_{\text{P}-Q} \) might have resulted in different CVQ because of variations in, for example, mean streamflow or magnitude of streamflow anomalies due to dissimilarity in storage characteristics. Also, glacier characteristics vary with respect to, for example, their water retention capacity (e.g., Jansson et al., 2003; Hock et al., 2005) or aspect (e.g., Hock, 2003, 2005), which influences the balance of \( Q_{\text{gl}} \) and \( Q_{\text{nongl}} \) on shorter or longer timescales and could cause the scatter in the CVQ and \( r_{\text{P}-Q} \) and \( r_{\text{T}-Q} \) for catchments with similar \( g \). The correlations might therefore only be a very rough indicator of a catchment’s location relative to the GCE optimum.

We showed that a universal relationship between CVQ and \( g \) in the Alps that could be used for quantitative planning does not exist. A space-for-time interpretation of the curves postulated by Chen and Ohmura (1990) and Fountain and Tangborn (1985) is not advised based on our analyses for two reasons: (a) In our intraregional analysis of streamflow observations, we could not find a distinct relation between CVQ and \( g \) following a theoretical GCE curve, and (b) changes over time of CVQ do not follow one common curve and also the relation itself is not stable over time. Possible reasons for the differences between our study and Chen and Ohmura (1990) could be the different time periods analysed. We chose a common period for all catchments (1976–2015), whereas Chen and Ohmura (1990) took different lengths of time series as available for the different catchments. If a different time period had caused the different results, this would mean that the relationship is not stable over time. However, redoing the exact same analyses as Chen and Ohmura (1990) with the same catchments for the same period, we found that some catchments were apparently not included in the fit of the curve given by Chen and Ohmura (1990) although being mentioned in their paper (Figure 9). We do not know the reason for leaving those out, but it might have influenced the results.

Relative glacier cover might not be the best indicator of the balance between the two runoff regimes in a partly glacierized

\[ \text{FIGURE 8} \quad \text{Relation between CVQ and } g \text{ for different 20-year time periods for } Q_{\text{ann}}. \text{ Left shows the multicatchment data set, right the nested model catchments. A second-order polynomial was fitted through the points. Only catchments that have streamflow data for both periods were used. The curve from Chen and Ohmura (1990) is plotted for comparison in the left panel. In the right panel, the GCE curve from the model experiment (40-year data) is shown in grey.} \]

\[ \text{FIGURE 9} \quad \text{Reconstruction of the GCE curve by Chen and Ohmura (1990). Overlapping catchments in our study with Chen and Ohmura (1990) were plotted for the same time period. CVQ was calculated for annual streamflow, Hydrological years (HY), summer months June, July and August (JJA), and summer half year (MJAS). CVQ is expressed as fraction, not percentage. Grey lines indicate catchments that were listed in the data section of Chen and Ohmura (1990) but not included in the figure of the quadratic fit.} \]
catchment. When glaciers melt due to warming, they may thin, the snow and firm reservoirs on the glaciers may reduce, and the accumulation ablation ratio can change (e.g., Dyurgerov, 2003; Paul, Klämb, & Haeberli, 2007), all before notable decreases in $g$ occur. These changes, however, could influence the amount of $Q_{gl}$. These processes might play a role when comparing different catchments with similar $g$ and when analysing changes over time for a particular catchment. Thus, also the balance of the glacier with climate can influence the GCE. A more balanced glacier has a different $Q_{nl}$ component than a glacier that is out of balance (e.g., Pritchard, 2019). European glaciers experienced close to balanced conditions around 1960–1980 (e.g., Vincent et al., 2017). The period analysed in Chen and Ohmura (1990) mostly covers this rather stable period, whereas the more recent period used in this study (1976–2015) is characterized by negative mass balances and retreating glaciers (Huss, Bauder, Funk, & Hock, 2008).

Our results correspond to some earlier studies. Farinotti, Uesselmann, Huss, Bauder, and Funk (2012) also found no clear pattern of $CV_Q$ and $g$ when modelling streamflow of several glacierized catchments for 1900–2100, allowing glaciers to retreat, and considering aggregated results for all catchments. Zhang et al. (2016) also found no quadratic GCE relationship, but instead plotted a power law function through 24 catchments in the Tian Shan Mountains. The results of Collins (2006b) for deglaciating catchments in the Alps show similar patterns compared with some of the selected Swiss catchments with long time series in our study (Figure 7). Comparing the streamflow of 1956–1980 with 1981–2005, he found an increase in $CV_Q$ for catchments with a high $g$ and a decrease for catchments with a low $g$, which contradicts a GCE curve pattern. Our data showed a shift in the $y$-values of the GCE curve over time, especially for the modelled catchments (Figure B, right), but also a shift of $GCE_{opt} (x$-axis) might be possible if the $Q_{nl}$ component becomes more dominant without a change in $g$. This could happen, for example, if rainfall in the non-glacierized part decreases, or if there will be less snow cover on the glacier. Both potential directions of change of the relationship strongly limit its use for planning and indicate that processes involved in the glacier compensation effect are complex.

4.2 Limitations and other controls on GCE

The multicatchment analyses as well as the model experiment revealed a number of limitations for the analysis of GCE. For example, undisturbed streamflow observations from high-glacierized catchments are rare. Such data are, however, important for analysing the right part of a potential GCE curve, particularly the steepness of this part of the curve. The Vernagtbach catchment ($g = 73.5\%$) proved its importance in our analysis, as well as in the study of Chen and Ohmura (1990), but it might be a unique catchment due to its small elevation range and a glacier that has retreated to a half-circle shape (with different aspects) and that has known surging behaviour (Hoinkes, 1969). Furthermore, the lack of observations of glacier cover at different historical times limits the combined analyses with long streamflow records.

In the study area, observed decreases in $g$ over the time periods covered by streamflow and glacier area observations are rather small (in the order of 5–10%). That makes it difficult to attribute changes in observed streamflow variability to changes in glacier cover. The few catchments with long time series only represent a small part of the theoretical curve. Glaciers adjust their size and elevation distribution to be in balance with climate, that is, in a warming climate, they retreat to higher elevations. These adjustments affect $Q_{gl}$ and $Q_{non-gl}$ and the GCE may depend on glacier mass balance and on the phase of peak glacier melt water (e.g., Huss & Hock, 2018; Immerzeel, Pellicciotti, & Bierkens, 2013). Another modelling experiment would be needed to analyse how the streamflow variability of (different) high-glacierized catchments develops over time when the glacier is retreating and even disappears (and the climate is changing) (e.g., Hagg, Braun, Kuhn, & Nesgaard, 2006; Nolin, Phillippe, Jefferson, & Lewis, 2010). Our results suggest that each catchment may have an individual GCE curve (Figure 7) with a different optimum and a different level of $CV_Q$ values. However, during glacier retreat, even the temporal trajectories of individual catchments may not follow a fixed GCE curve due to simultaneous changes in glacio-hydrological processes and climate characteristics.

It is important to note that total streamflow in the model experiment was separated in streamflow components from the glacierized and the non-glacierized part (Figures 4 and 5) but with runoff from snowmelt included in both. Snow depends both on precipitation (deposition) and temperature (melt), so it influences the non-glacierized part and the glacierized part of the catchment. Collins (2006a, 2006b) and Moore (1992) discuss the importance of the interannual variability of snow on the GCE. In warm summers following dry winters, the snow line rises sooner and higher up-glacier, allowing more ice to melt over a larger area compared with years with cool (or also warm) summers following snowy winters. In addition, in long time series of streamflow, not only relative glacier cover can change but also the area of bare ice when the snow line rises transiently (Collins, 2006b; Dahlke, Lyon, Janssen, Karlin, & Rosqvist, 2014; Hock et al., 2005). Thus, the role of snow in the GCE is complicated. Further studies addressing particularly the role of snow within the GCE context could give more insights in the interannual streamflow variability that is not explained by glacier cover alone.

We explored potential relations with some other catchment characteristics that may explain the variability in the empirical relations of $CV_Q$ values with $g$ (Figures S1 and S2). Elevation characteristics, temperature, and catchment area showed some effect on $CV_Q$. Mean elevation and temperature are however also related to $g$. Further model experiments and sensitivity analyses could give insights in the importance of other characteristics on streamflow variability in glacierized catchments, if models are able to represent hydrological (e.g., evapotranspiration and groundwater storage) and glaciological processes (glacier dynamics) in glacierized and non-glacierized catchments well.

Besides snow and catchment characteristics, antecedent conditions (for monthly flows) and changes and/or differences in climate characteristics might also be relevant to take into account. Annual
mean temperature has been increasing over our analysed period, and precipitation amounts have been rather stable or slightly increasing. However, the variability of T and P was fluctuating over time. If these fluctuations are large, glacier cover cannot compensate for them and changes in CVQ are then not only glacier cover related but also climate related (Collins, 2006a; Fleming et al., 2006). Another aspect of climate that could be important is the type of summer weather (Casassa et al., 2009; Moore, 1992). Moore (1992) suggests that in catchments with dry summers, in contrast to catchments with wet summers, the negative correlation between Qgl and Qnongl is more pronounced. In the Alps, the catchments have wetter summers compared with the summers in coastal North America, where most of the other studies on streamflow variability were conducted (e.g., Fleming & Clarke, 2005; Fountain & Tangborn, 1985; Moore, 1992). Combining different climatic influences within one regional sample may obscure a clear GCE curve. In our analysis, precipitation seasonality is similar for all catchments, but the relatively wet summers and varying precipitation amounts might complicate the search for a GCE curve. Related to that is the question of how the GCE appears in unstudied climates with distinctly differing amounts of precipitation and glacier melt and their interaction, possibly resulting in a different shape of a GCE curve. Moreover, we might need to think of a relationship for the compensating effect of glaciers that also includes climate characteristics on the axes (like the Budyko curve) to be robust for changes in climate that are not only influencing g, and to distinguish different climates. Such a relationship would then better allow for space-for-time substitution interpretations.

5 | CONCLUSION

This study analysed the potential to identify a universal relationship between glacier cover and interannual streamflow variability using complementary analyses of empirical data and a model experiment. The nested catchment model experiment resulted in a characteristic convex GCE curve confirming the theory that streamflow variability is dependent on relative glacier cover. In this idealized case, the relative glacier cover determines if precipitation or temperature dominates streamflow variability as shown by the correlation of streamflow with precipitation and temperature. The optimum glacier cover corresponding to the lowest interannual streamflow variability derived from the model experiment was around 10% or 15% glacier cover, for annual and August streamflow, respectively. In contrast, the empirical analysis based on real observations from a multicatchment data set showed a considerable scatter, especially the hypothesized increased streamflow variability with increasing glacier cover was not evident.

Comparing the GCE curve from the multicatchment data with that from the model experiment shows that relative glacier cover does not completely overrule other factors that could influence streamflow variability, such as other catchment or glacier characteristics. This means that a relationship fitted to data from some (modelled) catchments cannot be transferred to catchments with other characteristics. Our results also showed that the relationship between glacier cover and interannual streamflow variability can change over time and that individual catchments do not clearly follow one curve over time. Differences between our results and previously published relationships shed doubt on the existence of an ideal and simple universal relationship between streamflow variability of different catchments with different glacier cover and therefore on the validity of the use of such a GCE curve for estimating streamflow variability in glacierized catchments. Consequently, one needs to be careful about generalizing the role of glaciers as ideal buffers and assuming a characteristic GCE curve that can directly be used for space-for-time substitution applications.

DATA AVAILABILITY STATEMENT

Streamflow data from Austria are openly available from the eHYD database at https://ehyd.gv.at/. Swiss streamflow data were provided by the Swiss Federal Office for the Environment (FOEN) and available there on request. Climate data were made available by Zentralanstalt für Meteorologie und Geodynamik (ZAMG) and Meteoswiss, for Austria and Switzerland, respectively and are available on request from these institutions. Data were used under license for this project and study. Glacier outline data are available according to the given references.

ORCID

Marit van Tiel https://orcid.org/0000-0002-4819-337X
Irene Kohn https://orcid.org/0000-0002-8099-867X
Anne F. Van Loon https://orcid.org/0000-0003-2308-0392
Kerstin Stahl https://orcid.org/0000-0002-2159-9441

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SUPPORTING INFORMATION

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**APPENDIX**

**TABLE A1** Multicatchment data set for empirical analyses sorted by glacier cover. *g* is based on 2010/2012, climate data is based on 1961-2016

| Catchments | Country | River | Catchment area (km²) | Glacier area (km²) | Glacier Cover (%) | Mean elevation (m a.s.l.) | Elevation range (m) | Mean annual P [mm/year] | Mean annual T (°C) | Streamflow data |
|------------|---------|-------|----------------------|-------------------|------------------|--------------------------|---------------------|-------------------------|-----------------|----------------|
| Glacierized                                      |
| Vernagtac  | AT      | Vernagtbach  | 11.5                 | 8.4               | 73.5             | 3122                     | 973                 | 1125                    | −4.9            | 1974–2015      |
| Blatten bei Natenscd | CH  | Massa       | 195.5                | 110.6             | 56.6             | 2937                     | 2741                | 2374.4                  | −3.1            | 1922–2016      |
| Gletschc   | CH      | Rhone       | 39.4                 | 16.5              | 41.8             | 2709                     | 1860                | 2036.5                  | −2.6            | 1956–2016      |
| Hinterbichi UW | AT  | Isel        | 35                   | 13.65             | 39               | 2591                     | 1955                | 1483.2                  | −2.4            | 1951–2015      |
| Ventc      | AT      | Rofenache   | 98.1                 | 32                | 32.7             | 2890                     | 1873                | 976.6                   | −3.4            | 1967–2015      |
| Ochsenhütte | AT   | Hochalmbach | 8.73                 | 2.6               | 29.9             | 2663                     | 1356                | 1562.9                  | −2              | 1961–2015      |
| Innerschlöss | AT   | Gschlössbach | 40                   | 11.3              | 28.4             | 2463                     | 2139                | 1723.5                  | −1.7            | 1951–2015      |
| Obergurgl  | AT      | Gurgler Ache | 73                   | 19                | 26               | 2782                     | 1629                | 984.8                   | −2.6            | 1966–2015      |
| Blattencd  | CH      | Longa       | 77.4                 | 19.1              | 24.7             | 2620                     | 2376                | 1758.7                  | −2.1            | 1956–2016      |
| Oberfeld/Lenked | CH | Simme   | 34.8                 | 7.8               | 22.5             | 2341                     | 2147                | 1892.7                  | −1.1            | 1944–2016      |
| Erstfeld-Bodenbergc | CH   | Alpbach     | 20.7                 | 4.1               | 19.6             | 2193                     | 2170                | 1619.3                  | 0.6             | 1960–2016      |
| Matreier Tauernhaus | AT   | Tauernbach  | 60.28                | 11.33             | 18.8             | 2463                     | 2139                | 1675.1                  | −0.9            | 1951–2015      |
| Sulzau      | AT      | Obersulzbach| 80.8                 | 14.3              | 17.7             | 2298                     | 2772                | 1603.8                  | 0.1             | 1961–2015      |
| Huben       | AT      | Öztaler Ache| 516.9                | 80.7              | 15.6             | 2621                     | 2577                | 972.6                   | −1.7            | 1976–2015      |
| Pontresinabcd | CH   | Berninabach | 106.9                | 15.3              | 14.4             | 2614                     | 2214                | 1242.4                  | −2.2            | 1954–2016      |
| Gsteigc    | CH      | Lütschine   | 380.7                | 51.4              | 13.5             | 2040                     | 2308                | 1809.3                  | 0.6             | 1908–2016      |
| Zweilütschinenf | CH   | Weisse Lütschine | 164.9              | 21.5              | 13.1             | 2150                     | 3495                | 1848.6                  | 0.3             | 1933–2016      |
| Spöttling-taurer | AT   | Teilschnitzbach | 14                 | 1.8               | 13.1             | 2295                     | 2722                | 1263.8                  | −1.7            | 1976–2015      |
| Neukirchen  | AT      | Untersulzbach| 40.5                 | 4.9               | 12.1             | 2167                     | 2441                | 1496.1                  | 0.9             | 1971–2015      |
| Spöttling  | AT      | Kalserbach  | 47                   | 4.9               | 10.3             | 2594                     | 2295                | 1540                    | −0.9            | 1951–2015      |
| Neukaser   | AT      | Zanserbach  | 24.4                 | 2.1               | 8.6              | 2506                     | 1676                | 1387.6                  | −1.2            | 1976–2015      |
| Hinterbichl | AT   | Islit       | 107                  | 8.95              | 8.4              | 2538                     | 2164                | 1395.6                  | −1.5            | 1951–2015      |
| Waier      | AT      | Isel        | 285.3                | 22.9              | 8                | 2660                     | 2308                | 1279.4                  | −0.1            | 1951–2015      |
| IsenthalF  | CH      | Grosstalbach| 43.9                 | 2.9               | 6.7              | 1814                     | 2170                | 1768.1                  | 2.5             | 1956–2016      |
| Buochsbcd | CH      | Engelberger Aa | 228                | 5.6               | 2.5              | 1604                     | 2784                | 1813.4                  | 2.9             | 1916–2016      |
| Oberwil    | CH      | Simme      | 343.7                | 8.2               | 2.4              | 1635                     | 2466                | 1790.5                  | 0.6             | 1921–2016      |
| Sumvitg-Encardenscèd | CH | Sumvitg   | 21.8                 | 0.4               | 1.7              | 2447                     | 1670                | 1656.1                  | −0.9            | 1932–2016      |
| Catchments     | Country | River            | Catchment area (km²) | Glacier area (km²) | Glacier Cover (%) | Mean elevation (m a.s.l.) | Elevation range (m) | Mean annual P (mm/year) | Mean annual T (°C) | Streamflow data |
|----------------|---------|------------------|---------------------|-------------------|-------------------|---------------------------|---------------------|-------------------------|------------------|-----------------|
| St. Jodok      | AT      | Schmirnbach      | 108.8               | 0.9               | 0.8               | 2020                      | 2349                | 1172.2                  | 1.7              | 1951–2015       |
| Davos          | CH      | Dischmabach      | 42.9                | 0.3               | 0.65              | 2372                      | 1474                | 995.9                   | –0.7             | 1963–2016       |
| Hopfgarten     | AT      | Schwarzach       | 268.6               | 1.7               | 0.6               | 2451                      | 2066                | 1175                    | 0.1              | 1951–2015       |
| Mallnitz       | AT      | Mallnitzbach     | 85.3                | 0.4               | 0.5               | 2040                      | 2183                | 1289                    | 1.5              | 1961–2015       |
| Puig           | AT      | Sill             | 341.8               | 1.2               | 0.4               | 1910                      | 2465                | 1187.9                  | 2.3              | 1951–2015       |
| Steinach       | AT      | Gschnitzbach     | 111.4               | 0.3               | 0.3               | 1952                      | 2190                | 12637                   | 2.1              | 1951–2015       |
| La Punta-Chamues-ch1 | CH       | Chamuerabach     | 73.4                | 0.05              | 0.07              | 2547                      | 1536                | 1084.9                  | –2.1             | 1954–2016       |
| Zernez         | CH      | Ova da Cluozza   | 27                  | 0                 | 0                 | 2366                      | 1641                | 940.6                   | –1.2             | 1961–2016       |

**Non-glacierized**

| Catchments     | Country | River | Catchment area (km²) | Glacier area (km²) | Glacier Cover (%) | Mean elevation (m a.s.l.) | Elevation range (m) | Mean annual P (mm/year) | Mean annual T (°C) | Streamflow data |
|----------------|---------|-------|----------------------|--------------------|--------------------|---------------------------|---------------------|-------------------------|------------------|-----------------|
| Emmenmatt      | CH      | Emme  | 443.02               | 0                  | 0                  | 1064.8                    | 1579                | 1600                    | 6.2              | 1974–2015       |
| Sensematt      | CH      | Sense | 351.17               | 0                  | 0                  | 1071.9                    | 1626.3              | 1446                    | 6.3              | 1961–2015       |
| Adelboden      | CH      | Allenbach | 28.79               | 0                  | 0                  | 1863.2                    | 1434.5              | 1654                    | 2.9              | 1961–2015       |
| Eggiwil        | CH      | Emme  | 124.36               | 0                  | 0                  | 1281.2                    | 1607.6              | 1676                    | 5.1              | 1975–2015       |

**Note:**

- g is based on 2010/2012; climate data is based on 1961–2016.
- a Infilled winter streamflow data.
- b Possibly influenced (e.g., hydropoaking).
- c Overlapping catchment with CO1990 study.
- d Catchment with long time series used for CVQ changes over time (Figure 7).