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# Importance of maximum snow accumulation for summer low flows in humid catchments

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## Abstract

The expected increase of air temperature will increase the ratio of liquid to solid precipitation during winter and, thus decrease the amount of snow, especially in mid-elevation mountain ranges across Europe. The decrease of snow will affect groundwater recharge during spring and might cause low streamflow values in the subsequent summer period. To evaluate these potential climate change impacts, we investigated the effects of inter-annual variations in snow accumulation on summer low flow and addressed the following research questions: (1) how important is snow for summer low flows and how long is the "memory effect" in catchments with different elevations? (2) How sensitive are summer low flows to any change of winter snowpack? To find suitable predictors of summer low flow we used long time series from 14 alpine and pre-alpine catchments in Switzerland and computed different variables quantifying winter and spring snow conditions. We assessed the sensitivity of individual catchments to the change of maximum snow water equivalent ($SWE_{max}$) using the non-parametric Theil–Sen approach as well as an elasticity index. In general, the results indicated that maximum winter snow accumulation influenced summer low flow, but could only partly explain the observed inter-annual variations. One other important factor was the precipitation between maximum snow accumulation and summer low flow. When only the years with below average precipitation amounts during this period were considered, the importance of snow accumulation as a predictor of low flows increased. The slope of the regression between $SWE_{max}$ and summer low flow and the elasticity index both increased with increasing mean catchment elevation. This indicated a higher sensitivity of summer low flow to snow accumulation in alpine catchments compared to lower elevation catchments.





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## 1 Introduction

The shift from snowfall to rain is one of the most important effects of predicted climate change (Feng and Hu, 2007; Laghari et al., 2012; Berghuijs et al., 2014; Zhang et al., 2015). This shift results in a decrease of the fraction of solid precipitation (snow/total precipitation, known as S/P) and thus the decrease of snow accumulation especially in mid-elevation mountain ranges (Knowles et al., 2006; Pellicciotti et al., 2010; Speich et al., 2015). The decrease of S/P will affect groundwater recharge during spring and might influence low streamflow values in the subsequent summer period (Bavay et al., 2009; Berghuijs et al., 2014).

For the western US the decrease of S/P in low and middle elevations during the last decades could be explained mainly by an increase of air temperature during wet days in winter (Knowles et al., 2006). The simultaneously found change in winter precipitation for that region explained only a minor part of the decrease in S/P (Feng and Hu, 2007). For this region the largest decrease in S/P was found in March leading to the conclusion that an air temperature increase from December to March has the largest impact on snow accumulation, while warming from April to June rather affects snowmelt onset, dynamics and melt-out (Knowles et al., 2006; Feng and Hu, 2007).

Serquet et al. (2011) used the ratio of snowfall days and precipitation days (SD/PD) to assess the effect of air temperature increase on snowfall in Switzerland. They found decreased SD/PD over the last three decades especially in lower elevations. The decrease in SD/PD was stronger in spring than in winter (Serquet et al., 2011).

Berghuijs et al. (2014) showed that the higher fraction of precipitation fallen as snow is associated with higher long-term mean streamflow in comparison with catchments with lower snowfall fraction. Higher air temperatures during spring affect the onset of snowmelt streamflow shifting it towards earlier spring (Barnett et al., 2005; Dankers and Christensen, 2005; Lundquist and Flint, 2006; Hanel et al., 2012; Godsey et al., 2014; Langhammer et al., 2015). These changes lead to a higher fraction of annual flow occurring earlier in the water year as evident from many studies across the west-





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ern US (Cayan et al., 2001; Stewart et al., 2005; Day, 2009). However, snowmelt and consequent spring streamflow are affected by a wide range of factors, such as topography, vegetation and connected radiation as well as shading effects which might overlay the effect of increasing air temperature (Jost et al., 2007; Jenicek et al., 2012; Pomeroy et al., 2012; Kucerova and Jenicek, 2014). Earlier onset of snowmelt could, for instance, be slowed down by less shortwave radiation due to lower sun inclination in early spring (Lundquist and Flint, 2006).

While an increase of mean monthly runoff and low flows during winter and spring months were documented in several catchments in Switzerland and in other central European countries (Birsan et al., 2005; Fiala et al., 2010; Kliment et al., 2011), a significant decreasing trend of mean monthly discharge during winter was detected at selected mountain catchments in Slovakia (Blahusiakova and Matouskova, 2015).

Speich et al. (2015) demonstrated the sensitivity of catchments in the Swiss Alps to the reduction of snow contribution to total runoff by applying bivariate-mapping techniques. The elevation bands above 1000 m a.s.l. and below 2500 were found to be more sensitive to future temperature and precipitation scenarios than lower elevation catchments. Zappa and Kan (2007) demonstrated that the presence of above-average snow resources contributed to mitigating the effects of the 2003 summer drought in some high-elevation areas within the Swiss Alps.

Snow conditions in winter can effect low flows during the subsequent summer especially in areas with large differences in winter and summer precipitation. The total amount of snow precipitation in winter affects groundwater recharge and hence also runoff during dry summer periods (Earman et al., 2006; Beaulieu et al., 2012; Van Loon et al., 2015). While meteorological drivers and overall catchment storage both affect the drought duration during summer, seasonal storage in snow and glaciers affect the drought deficit (Van Loon and Laaha, 2015). However, the snow cannot solely explain the sensitivity to drought, although higher elevation catchments are generally less sensitive to drought origin, as some modelling experiments have shown larger





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groundwater storages in higher elevation Swiss catchments (Staudinger and Seibert, 2014; Staudinger et al., 2015).

Based on historical records from selected Sierra Nevada catchments, every 10 % decrease in snow water equivalent maximum in spring leads to a decrease of 9–22 % in minimum runoff during summer months and the runoff minimum occurs about 3–7 days earlier (Godsey et al., 2014). Higher elevation catchments showed a longer memory effect than lower elevation catchments (Cayan et al., 1993) and an effect of the snowpack of the preceding year on the subsequent summer runoff was found for some catchments in the Sierra Nevada mountains (Godsey et al., 2014).

The above mentioned results show that the influence of snow amount on early spring discharge is widely studied and known. However, we still lack a quantitative assessment of the sensitivity of summer low flows on snow conditions from the preceding winter. In this study the aim was (1) to quantify the length of the memory effect of individual catchments in terms of the influence of winter snow conditions on summer low flows and (2) to estimate the sensitivity of the catchments to changes in snowpack. Our study adds to earlier studies, by focusing on the combined effect of snow and summer precipitation and their varying spatial and temporal influence. To explore this combined effect is important especially in humid regions as most studies were performed in climates with more seasonal precipitation and/or smaller precipitation amounts overall. Moreover, we describe different sensitivity of low flows to varying snow conditions in catchments with different properties.

## 2 Material and methods

### 2.1 Study area

We selected 14 alpine and pre-alpine catchments in Switzerland with a catchment area from 0.93 to 1577 km$^2$ (Fig. 1 and Table 1). Catchments as close as possible to natural conditions were selected to minimize the effect of human activity on runoff. Further,





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in the studied catchments there is mostly zero or only a very small area covered by glaciers (0–2 %, with the exception of up to 4 % for Vorderrhein and Simme).

## 2.2 Data

Daily gridded precipitation and air temperature data (2 km by 2 km resolution), which were obtained from the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss; Frei and Schär, 1998; Frei, 2014), were averaged over the catchment area for use in the analyses. Daily snow water equivalent (SWE) data were also available as a gridded dataset with a 1 km by 1 km resolution. The SWE was calculated based on daily snow depth observations and a snow density model (Jonas et al., 2009) using interpolation and post-processing procedures first presented in Jörg-Hess et al. (2014). In a first step, available station data were mapped to a grid using de-trended distance weighting procedures that were specifically adapted to interpolate SWE data. To further account for changes in the number of available snow stations, the gridded dataset was homogenized using the quantile mapping method. Quantile mapping is a statistical calibration method that allows a set of maps to be improved based on fewer stations, by accounting for persistent spatial patterns in maps that are based on a larger number of stations. This procedure resulted in a homogenized dataset that covers the period 1971–2012, and the months November to May respectively. This same data set has already been adopted to update initial conditions of a hydrological model used for ensemble monthly predictions of SWE and runoff (Jörg-Hess et al., 2015). Further details on the methodology used to process the SWE data are available in Jörg-Hess et al. (2014), which further assessed the accuracy of the homogenized maps. Additionally, authors showed the first usage of this SWE data to assess the influence of snow conditions on summer low flows for a large Swiss catchment.

Daily discharge data were obtained from the Swiss Federal Office for the Environment (BAFU). Data from 1971 to 2012 were used in all analyses with the exception of a few shorter time series, as specified in Table 1.





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## 2.3 Statistical analysis and assessment

We selected different predictors related to winter and spring meteorological conditions and water storage conditions in the catchments (Table 2).

These predictors were tested to explain the variability of three variables describing low flow conditions: (i) minimum 7 day moving average of daily discharge was calculated based on BAFU data. Different sizes of the moving window (3, 7 and 15 days) were tested without significant influence on the results. (ii) The day of year of 7 day minimum of discharge was calculated from June to September to exclude low flows before snowmelt or after the onset of new winter snow accumulation. (iii) Number of days below a specified discharge threshold (25 % quantile of discharge from May to October).

We used eight variables as predictors of future summer low flows (Table 2). The maximum SWE before snowmelt onset was calculated using the above described SWE data from February to May in order to represent late winter snow conditions. We used both the maximum SWE calculated as a catchment mean and the maximum SWE calculated from the highest 50 % of catchment area, assuming that snowpack at higher elevations melts later and could be more important for summer discharges. The sum of positive SWE changes (sum of new snow) and the sum of positive air temperatures were used as well. Both variables were calculated as a sum from 1 November to 30 April.

While the variables related to snow describe the state of the individual catchment before snowmelt, total winter precipitation calculated from 1 November to 30 April describes the available water amount from winter precipitation. Additionally, we calculated the fraction of snowfall to total winter precipitation (S/P). Since information on whether precipitation occurred as rain or snow was not available, we used a threshold air temperature (1.1 °C) to determine the phase of precipitation.





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The day of year with maximum SWE was used to show the dependence of low flows on this variable. Using this, we could investigate if low flows occur later in the year and if they are higher with later occurrence of maximum SWE.

A current precipitation index $C_{PI}$ (Smakhtin and Masse, 2000) was used to describe the influence of preceding liquid precipitation on low flows. $C_{PI}$ was calculated for each month from June to September for the day when 7 day minimum discharge occurred (Eq. 1).

$$C_{PI(t)} = C_{PI(t-1)}K + P_t, \quad (1)$$

where $C_{PI(t)}$ [mm] is $C_{PI}$ for day $t$, $P$ [mm] is the catchment precipitation for day $t$ and $K$ [–] is the daily recession coefficient, which usually varies from 0.85 to 0.98 (Smakhtin and Masse, 2000). We used a $K$ value of 0.93 in this study. The statistical model used in our study is not sensitive to the exact value of $K$.

All parameters except $C_{PI}$ were calculated assuming a complete data series and considering only years with below-average spring and summer precipitation. The aim was to separate the effect of spring and summer liquid precipitation on low flows and thus highlight the effect of snow.

To assess the relations between predictors and response variables we used the Spearman rank correlation coefficient and the bivariate linear regression. Most of predictors and response variables were expressed as a percentage difference from the mean value, which enabled a comparison between individual catchments. The linear regression was computed from log-transformed variables. Prediction intervals of linear regression were used, which allowed the future observation of response variable to be estimated. The R software was used for all calculations in this study (http://www.r-project.org/).

The slope of regression calculated using the nonparametric Theil–Sen method was used to evaluate our statistical models. Theil–Sen slope is a median of slopes calculated for each pair of observations (Birsan et al., 2005; Pellicciotti et al., 2010). The higher the value, the steeper the slope of regression and thus the relation between





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independent (e.g. maximum SWE) and dependent variable (e.g. minimum discharge) is more obvious. The Theil–Sen linear regression model is suitable for non-normally distributed data with outliers.

The elasticity index (Eq. 2) was used to describe how sensitive the minimum discharge is to the change of SWE. The climate elasticity is often used to describe sensitivity of streamflow to the change of climate variables (Andréassian et al., 2015). A similar concept was used in this study to describe what percentage change of minimum discharge is caused by a defined percentage change of maximum SWE (Eq. 2).

$$\text{Elasticity} = \text{\% change of minimum discharge}/\text{\% change of maximum SWE} \quad (2)$$

While the relationship between maximum SWE and minimum discharge is usually not linear, the elasticity index changes for different SWE conditions. The elasticity index in this study is usually lower than 1 which means that a particular percentage change in maximum SWE causes a lower percentage change of minimum discharge. The elasticity index was calculated from the 50 % probability of prediction derived from the individual linear models.

All analyses were done separately for each catchment and mostly for the period May to September. Analyses of the combined effect of snow and liquid precipitation were made only for the period from June to September, because liquid precipitation (expressed as $C_{\mathrm{Pl}}$) was not calculated for May. In May there is still snow in some catchments and including it in $C_{\mathrm{Pl}}$ would affect the interpretation of the results.

## 3 Results

### 3.1 Correlation of selected predictors and response variables

Spearman rank correlation coefficients were calculated both for the whole observation period and for selected years with below-average spring and summer precipitation (Table 3). This was done to separate the effect of snow and reduce the effect of liquid





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precipitation. This way we can conclude that snow is more important for low flows in May and June and its role decreases in August and September. In contrast, the importance of liquid precipitation on low flows generally increases from June to September. However, the snow remains important even in late summer in the case that there is below-average preceding precipitation (Table 3, "low $C_{\mathrm{Pl}}$").

The 7 day minimum discharge was predicted best by the sum of winter precipitation from 1 November to 30 April in the period from May to July. In August, maximum SWE predicts minimum discharge slightly better than winter precipitation (Table 3). The correlation between minimum discharge and S/P index was surprisingly weak with significant correlations (0.05 level) only in June and July. The day of year of 7 day minimum discharge could be correlated best with winter precipitation. The correlations are rather weak, although most of them are significant at the 0.05 level. There is a negative trend in the number of days with discharge below the specified threshold in case of increasing peak SWE, sum of new SWE and winter precipitation. The number of days with discharge below the specified threshold decreased as well with a later occurrence of peak SWE. Despite the significance of the correlations found, their values are not high which indicates that low flows are influenced by more than a single variable. Additionally, some of the predictors are not mutually independent.

### 3.2 Influence of maximum SWE on low flows

Snow melt affects groundwater recharge and thus it has an effect on low flow values even after the melt-out of the snowpack. However, groundwater data are usually not accessible at the catchment scale and have to be simulated. Thus, we used maximum SWE as a variable to predict 7 day minimum discharge (Fig. 2). A decrease of snow influence with time is seen in selected catchments representing different elevation ranges.

The relationship between the 7 day minimum discharge and maximum SWE (Fig. 2) are characterized by a large variability indicating that only a certain portion of low flow variability can be explained using the maximum SWE. Coefficients of determi-





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nation ($R^2$) were not higher than 0.65 for high elevation catchments during late spring and early summer. However, $R^2$ does not describe either an increasing or decreasing trend in the data. Therefore, the Theil–Sen slope of the regression and the elasticity index were used to describe the relationship between predictor and response variable (Figs. 3 and 4). Both Theil–Sen Slope and elasticity describe the sensitivity of low flows to both decrease and increase of maximum SWE compared to the mean value. The sensitivity of individual catchments strongly depends on catchment properties, such as mean catchment elevation, maximum SWE and S/P (Table 4). These correlations clearly varied for different months and reached their maximum in July and August and they decreased in September.

Theil–Sen slopes for each catchment and for every week from the beginning of May to the end of September, allowed an analysis of the memory effect of each catchment (Fig. 4). These weekly slopes describe how long water from snow melt contributes to runoff formation and thus how long snow affects low flows. With this approach, a significant effect of snow on low flows became visible during the whole summer and until September for catchments higher than 2000 m a.s.l. Snow affected low flows until July in catchments with mean catchment elevation in the range of 1500 to 2000 m a.s.l. However, snow did not affect summer low flow (July to September) in catchments lower than 1500 m a.s.l. Here, snow affected low flows during May and June only, which is probably caused mostly by lower SWE (maximum less than 250 mm).

The effect of high peak SWE is important for groundwater recharge and influences mainly the volume of water in the groundwater zone. The effect of elevation influences mainly the timing of snowmelt with later snowmelt onset in higher elevations. Thus, the water inflow into the groundwater zone occurs later in spring and it is distributed over a longer time period. Therefore, groundwater recharge from snow affects low flows even in late summer.

The elasticity calculated for the 50 % probability of prediction enables us to describe the impact of future changes of snowpack either due to natural annual variability or due to the predicted climate change (Fig. 5). In case of basins higher than 2000 m a.s.l.,





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every decrease of the maximum SWE by 10 % will cause a decrease of minimum discharge in July by 6 to 9 % (Fig. 5, top right). This means that the decrease of minimum discharge is almost proportional to the decrease of SWE in some cases (Ova Da Cluozza and Ova dal Fuorn). For catchments with a mean elevation between 1500 and 2000 m a.s.l., the decrease of minimum discharge ranges from 2 % (Grande Eau) to 5 % (Simme). The lowest catchments are characterized with even lower values indicating that any decrease of maximum SWE will not significantly affect low flows at least from July to September. However, there is some small effect during June (Fig. 5, top left). Generally, the sensitivity of low flows to the change of SWE increases with elevation and decreases from June to September. However, the elasticity is not linear and the decrease of low flows accelerates with decreasing SWE.

The volume of accumulated snow for each catchment impacted the day of year with minimum discharge (Fig. 6). The hypothesis was that minimum summer discharge would occur later in the year for higher peak SWE. However, later low flow occurrence may be additionally influenced by a later melt-out and thus later maximum of groundwater storage. Low flows occurred in September and October for higher elevation catchments with a higher SWE maximum. In contrast, July and August are typical months for low flow occurrences for lower elevation catchments with lower SWE maximum. On average, every decrease in peak SWE by 100 mm resulted in runoff minima occurring about 12 days earlier. However, inter-annual variability markedly increases in lower elevation catchments indicating an increasing role of summer precipitation.

### 3.3 Combined effect of snow conditions and preceding precipitation on summer low flows

Snow is an important component for groundwater recharge during the snowmelt period. However, the relation between snow and minimum discharge during the summer period is not often clear and may be overlaid by several other factors, mostly precipitation after melt-out. To demonstrate the combined effect of snow and precipitation on summer





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low flows, three snow-dominated catchments in high and middle elevations (Ova da Cluozza, Vorderrhein and Lümpenenbach) were selected and further analyzed.

For years with lower than average preceding precipitation, snow became a better predictor to explain the variability of minimum discharge indicated by steeper regression slopes and higher coefficients of Spearman rank correlation (Fig. 7, top). Minimum discharges did not decrease much with a low SWE and above-average preceding precipitation (top plots, blue lines). However, snow was more important for situations with low liquid precipitation. In these cases, minimum discharges were more sensitive to the change of summer precipitation (top plots, red lines).

The minimum discharge decreased significantly in years with lower than average SWE maximum and average preceding precipitation compared to years with higher than average SWE maximum and same amount of preceding precipitation (Fig. 7, bottom). For the Ova da Cluozza catchment, as an example, and considering only years with above-average SWE maximum, there is a 50 % probability that given an average preceding precipitation there will be a 7 day minimum discharge equal or higher than 107 % of its normal in July. On the contrary, considering years with below-average SWE maximum, the 7 day minimum discharge will decrease to 75 % of its normal level. Similar changes are predicted both for higher elevation catchments and lower elevation catchments, although in the latter this decrease is somewhat smaller.

The combined effect of snow and liquid precipitation on low flows was analyzed using "score plots". In these plots the position of each catchment is shown according to its average influence of snow and precipitation on the 7 day minimum discharge separately for the period from June to September (Fig. 8). The SWE score ($x$ axis) and $C_{\mathrm{PI}}$ score ($y$ axis) were calculated according to the following equations (Eqs. 3 and 4).

$$\mathrm{SWE}_{\mathrm{score}} = \sum_{i=1}^{n} (\mathrm{SWE}_i \times Q_{\mathrm{min}_i}/100)/n \quad (3)$$

$$C_{\mathrm{PI\ score}} = \sum_{i=1}^{n} (C_{\mathrm{PI}(i)} \times Q_{\mathrm{min}_i}/100)/n \quad (4)$$





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where $SWE_i$ is peak SWE in the year $i$, $Q_{\min_i}$ is the 7 day minimum discharge in the specific month of year $i$ and $C_{\mathrm{PI}(i)}$ is the current precipitation index on the day when $Q_{\min_i}$ occurs. All input values are expressed as a percentage difference from the mean (e.g. SWE equal to 100 %, means the average maximum of SWE in a catchment). The higher the score, the stronger the respective effect on low flows.

Points located below the $y = x$ line indicate catchments where snow has a stronger effect on low flows compared to rain. Catchments with a mean elevation higher than 1600 m a.s.l. in June and July and higher than 2000 m a.s.l. in August are typical representatives for a stronger effect of snow. Points located above the line indicate catchments with a stronger effect of rain on low flows (lower elevation catchments in June, July and August and all catchments in September).

# 4 Discussion

## 4.1 The role of catchment properties

We explored the dependencies of summer low flows on different meteorological predictors related to the winter period. Based on our results it seems that dependencies may be connected to catchment properties and climate drivers to some degree, such as elevation and thus maximum SWE and S/P. However, the variability of low flows cannot be explained by one single parameter, which are indicated by relatively low values of Spearman rank correlation (despite their prevailing significance at 0.01 level).

The correlation of the dependencies of summer low flows on catchment elevation can be explained by lower air temperature in higher elevation and thus more snow accumulation and may be supported by results of Birsan et al. (2005) and Staudinger et al. (2015) in Swiss catchments. Staudinger et al. (2015) showed that higher elevation and steeper catchments were less sensitive to droughts mainly because of an increasing snow influence but also because of potentially larger storages for the higher elevation catchments of the selection. Our results showed that this sensitivity might





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increase with decreasing SWE either due to natural annual variability or due to climate change.

The elevation was also related to the memory effect of individual catchments which was generally longer for the highest elevation catchments than for middle or low elevation catchments. However, even with the highest elevation catchments, we did not find any significant correlations of snow and minimum discharges in October and later. In contrast, Godsey et al. (2014) found significant correlations even with the previous year's snowpack for some catchments in the western US. Summer precipitation in Switzerland is relatively higher than summer precipitation in the western US and, as shown in our study, summer precipitation dominates over the effect of snow, especially with an increasing time from the snowmelt period, which explains the contrary results for the western US and Switzerland. We also found negative correlations between maximum SWE and low flows in few cases in low elevation catchments. However, these negative correlations cannot be explained by any physical process and they should be considered as a noise.

A longer memory effect in catchments with higher elevation is not only connected to higher snowpack accumulations but also to the simple fact that snowmelt occurs later in spring and persists longer compared to catchments in lower elevations (often until late spring or even early summer). The dependence of the day of year of peak SWE on day of year of minimum discharge was confirmed in our study. Similar dependences were found also in Whitaker et al. (2008), using the timing of the first significant snowmelt event instead of the day of year of peak SWE. A negative trend in the number of days with discharge below specified threshold in case of increasing peak SWE was proved. A 25 % quantile of discharge from May to October was used in this study. A 10 % quantile was also tested and found to have only minor impact on the results.

As documented by Beaulieu et al. (2012) in British Columbia, snow from headwater parts of catchments contributes significantly to base flow in lower parts of the catchments during summer. Earlier snowmelt onset and thus decrease of minimum streamflow has been observed (Jefferson, 2011) and a further shift of snowmelt towards ear-





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lier spring is predicted (Cayan et al., 2001; Barnett et al., 2005; Stewart et al., 2005; Bavay et al., 2009; Godsey et al., 2014).

## 4.2 Consequences of climate change

The influence of snow conditions on summer low flow will likely decrease due to predicted air temperature increase during winter and thus the decrease of S/P ratio and SWE in middle elevations. The snow fraction has an important effect on not only annual discharge (Berghuijs et al., 2014; Speich et al., 2015; Zhang et al., 2015) but also on summer low flows as documented by Godsey et al. (2014) in the western US and Laghari et al. (2012) in Austria. Our results are similar for catchments in Switzerland, and based on these studies, we may conclude that summer low flows are significantly sensitive to any SWE changes. Although, our study did not focus on existing trends in data, we expect a reducing effect of snow on late summer low flows in the highest elevation catchments. This reduction might increase problems with water availability in affected regions.

## 4.3 Combined effect of snow and precipitation

The correlation between minimum discharge and maximum SWE, considering years with little rain, was higher than in years with a lot of rain. Low flows are usually higher during years with above-average snow conditions. Even in the case of low antecedent precipitation, low flow was higher than in years with below-average snow conditions. Therefore, snow plays an important role, although below-average snow conditions do not necessarily indicate below-average low flows. Preceding precipitation seems to be more important in this case. Because of the combined effect of snow and summer precipitation on summer low flows, snow-related parameters cannot fully explain the annual variability of low flows as documented by Godsey et al. (2014) even for the highest elevation catchments. Nevertheless, most of detected trends in our study (using Theil–Sen slope) were significant at less than the 0.05 level.





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The decrease of SWE and snowfall fraction increased the relative importance of rain during summer and rain thus became a relatively more important source for groundwater recharge. A continuous decrease of SWE and snowfall fraction in the future might increase the sensitivity of catchments in mid and high elevations to hydrological droughts. This conclusion is in accordance with results of Birsan et al. (2005).

## 5 Conclusions

This study described the influence of winter and spring snow conditions on summer low flows. Specifically, we investigated the memory effect related to snow influence in runoff and the sensitivity of the catchments to low flow reduction due to any change of snowpack. The main conclusions are the following:

- Snow significantly affected low flows in May to September (with decreasing importance) for catchments higher than 2000 m a.s.l., up to, in July and August in mid-elevation catchments and only in June and July in the lowest elevation catchments.
- The sensitivity of low flows to maximum annual SWE was higher for catchments at higher elevation.
- Low flows occurred later in the year for years with above average snow accumulations. A decrease of maximum snow accumulations by 100 mm resulted in earlier runoff minima by 12 days.
- Snow and summer precipitation had a combined effect on summer low flows, and snow accumulation cannot alone explain the annual variability of low flows even in high-elevation catchments. Snow was a better predictor for the variability of low flows when only years with lower than average preceding precipitation were considered.





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– Smaller values for SWE and snowfall fraction were related to an increased relative importance of rain during summer for low flows. As a consequence the sensitivity of catchments in mid and high elevations to meteorological droughts might increase.

*Author contributions.* M. Zappa and J. Seibert initiated the project. M. Jenicek developed the methodology (with contributions of Jan Seibert) and performed all analyses. M. Zappa, M. Staudinger and T. Jonas prepared input meteorological data used for analyses. M. Jenicek prepared the manuscript with substantial contributions from all co-authors.

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**Table 1.** Study catchments and selected characteristics (S/P refers to the ratio of snowfall to total precipitation).

| Catchment (gauging station) | Area ($km^2$) | Mean elevation (m a.s.l.) | Elevation range (m a.s.l.) | Mean slope (°) | Mean $SWE_{max}$ (mm) | S/P [–] | Data period |
|---|---|---|---|---|---|---|---|
| Dischmabach (Davos) | 42.9 | 2368 | 1667–3138 | 22.9 | 484 | 0.97 | 1971–2012 |
| Ova Da Cluozza (Zernez) | 27.0 | 2361 | 1507–3160 | 26.8 | 339 | 0.98 | 1971–2012 |
| Ova Dal Fuorn (Zernez) | 55.3 | 2328 | 1706–3156 | 18.9 | 339 | 0.97 | 1971–2012 |
| Hinterrhein (Fürstenau) | 1577 | 2113 | 649–3406 | 21.9 | 333 | 0.91 | 1974–2012 |
| Vorderrhein (Ilanz) | 774 | 2023 | 691–3605 | 23.0 | 391 | 0.88 | 1971–2012 |
| Riale di Calneggia (Cavergno) | 23.9 | 1986 | 883–2911 | 29.1 | 423 | 0.88 | 1971–2012 |
| Allenbach (Adelboden) | 28.8 | 1851 | 1296–2753 | 19.7 | 351 | 0.78 | 1971–2012 |
| Simme (Oberwil) | 344 | 1632 | 776–3242 | 18.1 | 530 | 0.74 | 1971–2012 |
| Grande Eau (Aigle) | 132 | 1557 | 417–3204 | 21.1 | 249 | 0.71 | 1971–2012 |
| Lümpenenbach | 0.93 | 1318 | 1100–1515 | 15.1 | 323 | 0.59 | 1974–2012 |
| Emme (Eggiwil) | 124 | 1275 | 581–2220 | 14.2 | 185 | 0.59 | 1975–2012 |
| Sitter (Appenzell) | 74.4 | 1247 | 769–2501 | 17.8 | 193 | 0.62 | 1971–2012 |
| Sense (Thörishaus) | 351 | 1068 | 551–2181 | 9.9 | 95 | 0.39 | 1971–2012 |
| Gürbe (Belp) | 116 | 845 | 518–2169 | 8.7 | 52 | 0.41 | 1971–2012 |





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**Table 2.** Predictor and response variables used in analyses.

| Predictor variables | Response variables |
|---|---|
| Maximum of SWE during winter before melting (catchment mean) | Minimum of 7 day moving average of discharge |
| Maximum of SWE during winter before melting (SWE mean calculated from higher situated 50 % of catchment area) | Day of year with 7 day minimum of discharge |
| Sum of winter precipitation (Nov–Apr) | Number of days below specified runoff threshold (25 % quantile of runoff from May to Oct used) |
| Rate of snowfall vs. total winter precipitation (S/P) | |
| Sum of positive SWE changes from Nov to Apr | |
| Sum of positive air temperatures from Nov to Apr | |
| Current precipitation index $C_{PI}$ (Smakhtin and Masse, 2000) | |
| Day of year with maximum SWE | |





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**Table 3.** Spearman rank correlation coefficients for the relation between predictors (columns) and response variables (rows). Statistically significant correlations at the 0.05 level are marked in italic, correlations significant at the 0.01 level are also highlighted in bold. "All years" means that the whole observation period was taken into account, and "Low $C_{PI}$" means that only years with below-average precipitation were taken into account.

| Predictor/Response variable | $Q_{min}$ May | $Q_{min}$ Jun | | $Q_{min}$ Jul | | $Q_{min}$ Aug | | $Q_{min}$ Sep | | Day of year of $Q_{min}$ | No. days < $Q_{25\,\%}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | All years | All years | Low $C_{PI}$ | All years | Low $C_{PI}$ | All years | Low $C_{PI}$ | All years | Low $C_{PI}$ | All years | All years |
| $SWE_{max}$ | ***0.39*** | ***0.33*** | ***0.30*** | ***0.29*** | ***0.33*** | ***0.19*** | ***0.29*** | ***0.11*** | 0.13 | *0.10* | ***−0.25*** |
| $SWE_{max}$ – upper part | ***0.40*** | ***0.34*** | ***0.32*** | ***0.31*** | ***0.37*** | ***0.21*** | ***0.33*** | ***0.12*** | 0.14 | *0.10* | ***−0.27*** |
| Sum of new SWE | ***0.31*** | ***0.29*** | ***0.25*** | ***0.32*** | ***0.41*** | ***0.14*** | ***0.25*** | ***0.13*** | 0.11 | 0.08 | ***−0.26*** |
| Jul date of $SWE_{max}$ | ***0.17*** | ***0.18*** | ***0.21*** | *0.08* | ***0.21*** | ***0.17*** | ***0.21*** | 0.05 | *0.17* | *0.09* | ***−0.14*** |
| S/P | 0.08 | ***0.20*** | 0.09 | *0.09* | 0.10 | 0.03 | 0.14 | 0.04 | 0.13 | 0.08 | −0.05 |
| Sum of positive air temp. | −0.07 | ***−0.24*** | ***−0.23*** | ***−0.23*** | ***−0.23*** | ***−0.19*** | ***−0.23*** | *0.09* | ***−0.23*** | −0.08 | 0.00 |
| Winter precipitation | ***0.47*** | ***0.43*** | ***0.45*** | ***0.34*** | ***0.40*** | ***0.18*** | ***0.25*** | ***0.11*** | *0.16* | ***0.13*** | ***−0.24*** |
| $C_{PI}$ | – | ***0.36*** | – | ***0.44*** | – | ***0.43*** | – | ***0.53*** | – | ***−0.41*** | ***−0.37*** |





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**Table 4.** Spearman rank correlation coefficients for the relation between catchment properties and Theil–Sen slopes (TS), which were computed for assessing the low flow sensitivity to peak SWE. Statistically significant correlations (at the 0.05 level) are shown in bold.

| Catchment property | TS May | TS Jun | TS Jul | TS Aug | TS Sep |
|---|---|---|---|---|---|
| Area | 0.18 | 0.02 | −0.12 | −0.17 | 0.16 |
| Elevation | −0.09 | **0.58** | **0.88** | **0.80** | 0.52 |
| Slope | 0.07 | 0.28 | **0.83** | **0.73** | 0.49 |
| Maximum SWE | 0.00 | **0.67** | **0.60** | **0.57** | **0.66** |
| S/P | −0.13 | **0.62** | **0.87** | **0.84** | **0.54** |
| Winter precipitation | 0.41 | −0.29 | −0.32 | −0.39 | −0.17 |





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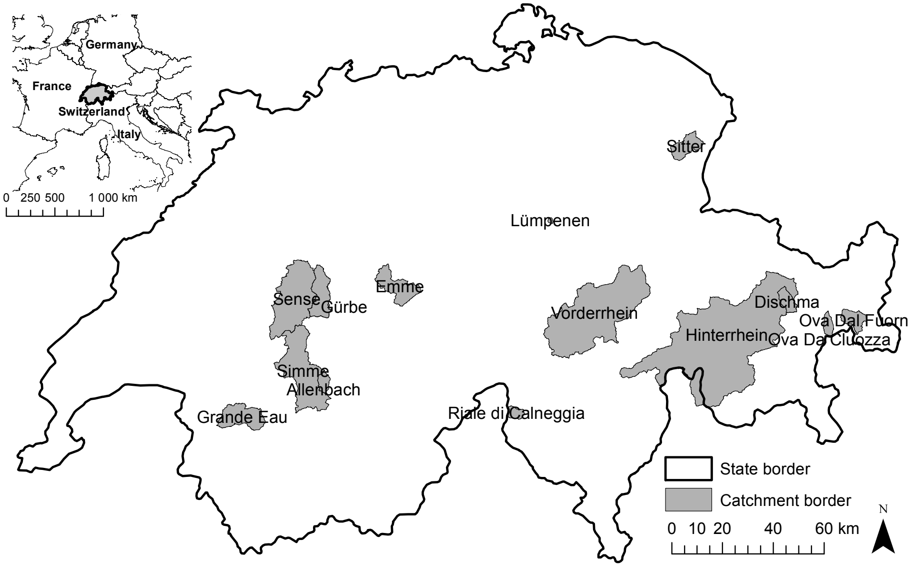


**Figure 1.** Location of the study catchments within Switzerland.





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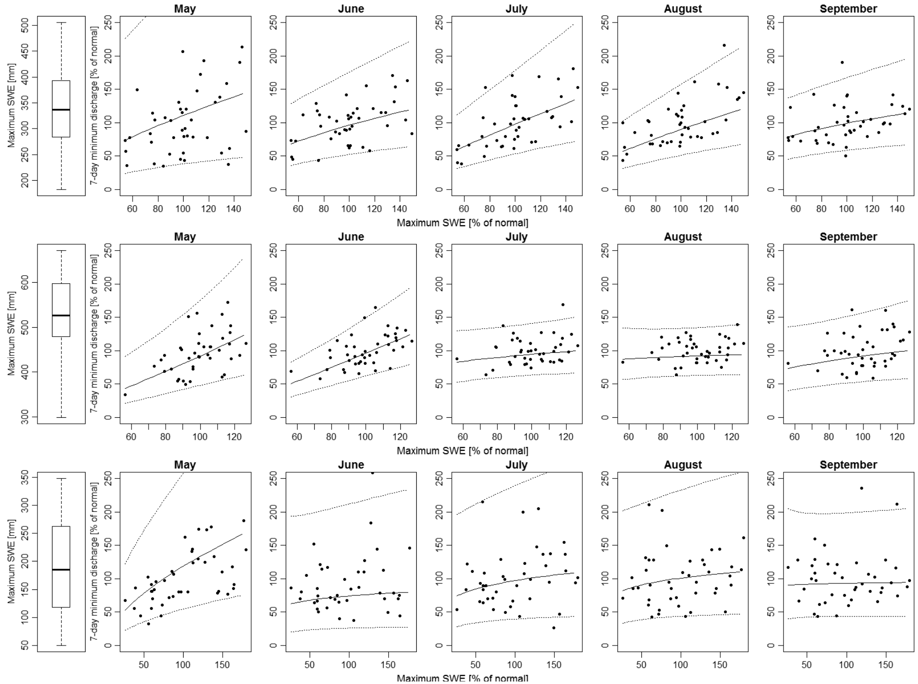


**Figure 2.** Dependence of 7 day minimum discharge on maximum SWE for individual months. Top: Ova da Cluozza River representing a high elevation catchment with a mean catchment elevation of 2361 m a.s.l., correlations from May to September are statistically significant (0.05 level). Middle: Simme River, representing a middle elevation catchment with a mean catchment elevation of 1632 m a.s.l., correlations from May to June are significant. Bottom: Sitter River as a representative of a low elevation catchment with a mean catchment elevation of 1247 m a.s.l., only the correlation in May is significant. Solid lines represent the low flow occurring with a 50 % probability, dotted lines represent the 95 % prediction interval.





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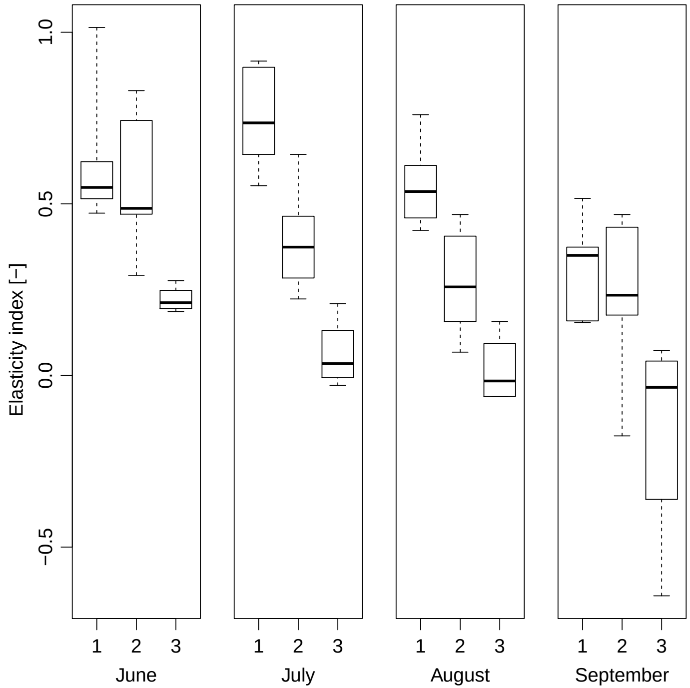


**Figure 3.** Elasticity index for all catchments classified according to elevation describing the sensitivity of 7 day minimum discharge on maximum SWE for individual months. Elevation classes on *x* axis: 1 – catchments with mean elevation higher than 2000 m a.s.l.; 2 – catchments with mean elevation between 1400 and 2000 m a.s.l.; 3 – catchments with mean elevation between 850 and 1400 m a.s.l. The boxes represent the 25, 50 and 75 % quantiles and the whiskers represent minimum and maximum values.





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| Basin | Elevation [m a.s.l.] | Week number (May to September) 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dischma | 2368 | **0.4** | **0.3** | **0.5** | **0.8** | **0.7** | **0.8** | **0.4** | **0.5** | **0.5** | **0.3** | **0.6** | **0.8** | **0.7** | **0.3** | **0.4** | **0.4** | **0.3** | **0.3** | 0.1 | 0.0 | 0.1 |
| Ova da Cluozza | 2361 | **0.6** | **0.6** | **0.5** | **0.9** | **0.3** | **0.5** | **0.6** | **0.6** | **0.4** | **1.0** | **0.9** | **1.1** | **0.9** | **1.1** | **0.8** | **0.7** | **0.5** | **0.7** | **0.4** | **0.5** | **0.4** |
| Ova dal Fuorn | 2328 | **0.7** | **0.5** | **0.9** | **0.9** | **0.9** | **0.6** | **1.0** | **1.2** | **0.9** | **1.2** | **1.0** | **0.9** | **0.6** | **0.6** | **0.5** | **0.6** | **0.7** | **0.6** | **0.4** | **0.3** | **0.4** |
| Hinterrhein | 2113 | **0.7** | **0.7** | **0.7** | **0.8** | **0.7** | **0.5** | **0.2** | **0.3** | **0.3** | **0.3** | **0.6** | **0.8** | **1.0** | **0.9** | **1.0** | **0.6** | **0.6** | **0.5** | 0.0 | 0.1 | **0.2** |
| Vorderrhein | 2023 | **0.6** | **0.6** | **0.5** | **0.6** | **0.3** | **0.5** | **0.2** | **0.2** | **0.5** | **0.5** | **0.6** | **0.7** | **0.8** | **0.7** | **0.6** | **0.4** | **0.5** | **0.6** | **0.5** | **0.5** | **0.7** |
| Riale di Calneggia | 1986 | **0.2** | 0.0 | 0.1 | **0.4** | -0.1 | **0.4** | **0.5** | **0.7** | **0.7** | **1.0** | **0.7** | **0.7** | **0.6** | **0.7** | **0.6** | **0.5** | **0.5** | 0.2 | 0.0 | **0.3** | 0.3 |
| Allenbach | 1851 | **0.8** | **0.7** | **1.0** | **1.1** | **1.0** | **0.9** | **1.0** | **0.8** | **0.4** | **0.2** | **0.3** | 0.2 | 0.2 | **0.6** | **0.7** | **0.5** | **0.4** | **0.3** | 0.1 | 0.0 | 0.2 |
| Simme | 1632 | **1.8** | **1.3** | **1.2** | **1.4** | **1.0** | **0.8** | **0.7** | **0.5** | **0.5** | 0.1 | 0.0 | 0.1 | **0.2** | 0.2 | 0.2 | -0.1 | 0.2 | **0.5** | **0.5** | **0.7** | **0.3** |
| Grande Eau | 1557 | **0.6** | **0.6** | **0.7** | **0.8** | **0.6** | **0.4** | **0.3** | **0.5** | **0.1** | 0.2 | 0.0 | **0.2** | **0.2** | **0.1** | **0.2** | 0.0 | **0.4** | **0.2** | **0.3** | **0.2** | **0.1** |
| Lümpenenbach | 1318 | **0.8** | **1.2** | **0.7** | **0.9** | **0.5** | **-0.3** | 0.3 | **0.2** | -0.1 | 0.0 | 0.1 | **0.8** | -0.1 | -0.2 | **0.2** | **0.4** | 0.5 | -0.1 | **-0.2** | 0.0 | 0.1 |
| Emme | 1275 | **0.7** | **1.0** | **0.7** | **0.8** | **0.4** | -0.1 | -0.1 | **0.2** | 0.0 | -0.5 | -0.2 | 0.0 | **-0.6** | **-0.6** | 0.1 | 0.2 | -0.5 | **-0.2** | -0.4 | **-0.6** | -0.5 |
| Sitter | 1247 | **0.5** | **0.6** | **0.5** | **0.7** | **0.6** | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 | 0.2 | 0.3 | -0.2 | **-0.3** | 0.1 | -0.1 | 0.1 | -0.2 | -0.1 | 0.1 | 0.0 |
| Sense | 1068 | **0.4** | **0.5** | **0.5** | **0.6** | **0.2** | -0.1 | **0.1** | **0.3** | **0.2** | 0.1 | **-0.2** | 0.1 | 0.0 | 0.1 | -0.2 | 0.1 | **0.2** | 0.1 | 0.0 | 0.1 | 0.4 |
| Gürbe | 845 | **0.3** | **0.2** | **0.4** | **0.4** | **0.4** | 0.1 | 0.0 | **0.2** | 0.0 | -0.1 | **-0.3** | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 |

**Figure 4.** Dependence of 7 day minimum discharge on maximum SWE for all studied catchments for individual weeks from the beginning of May (week 19) to the end of September (week 39). Numbers provide the Theil–Sen slopes between the variables. Significant correlations (0.05) are given in bold. Red indicates positive effect of SWE on minimum discharge (positive slopes), blue indicates negative effect of SWE on minimum discharge (negative slopes).





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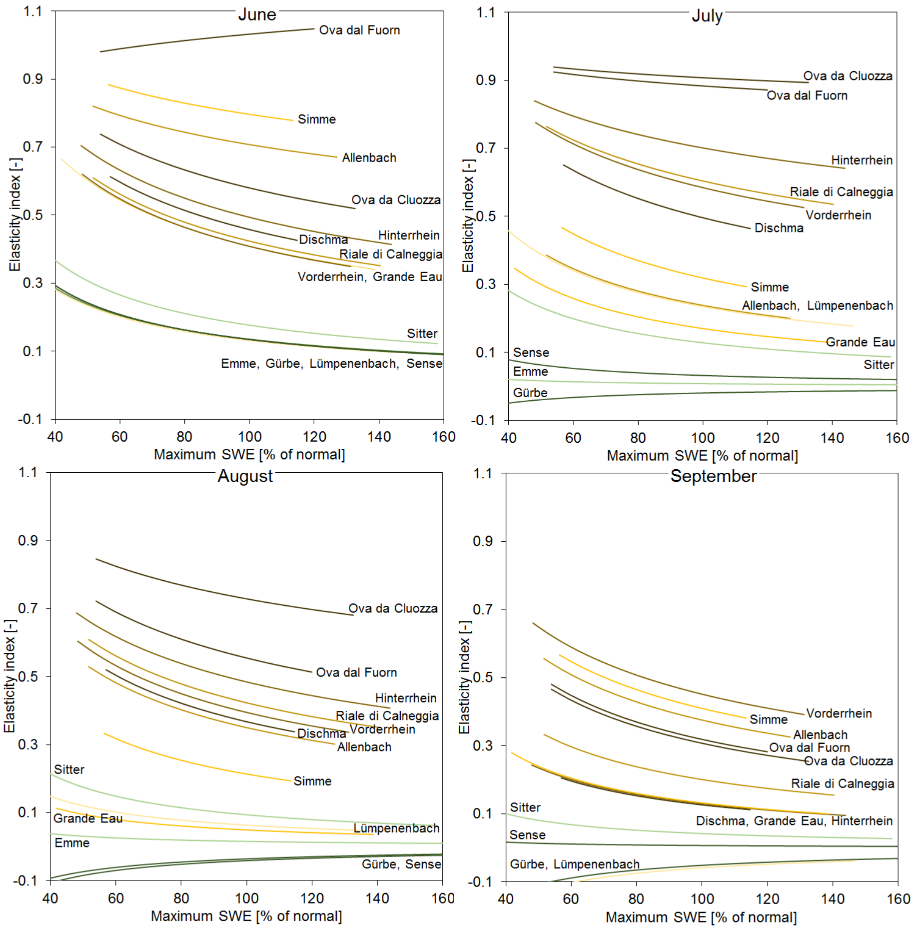


**Figure 5.** Elasticity index showing the sensitivity of minimum discharge to changes in SWE. The index was calculated from the 50 % probability of prediction. Line colors indicate the catchment mean elevations (dark brown: highest; dark green: lowest).





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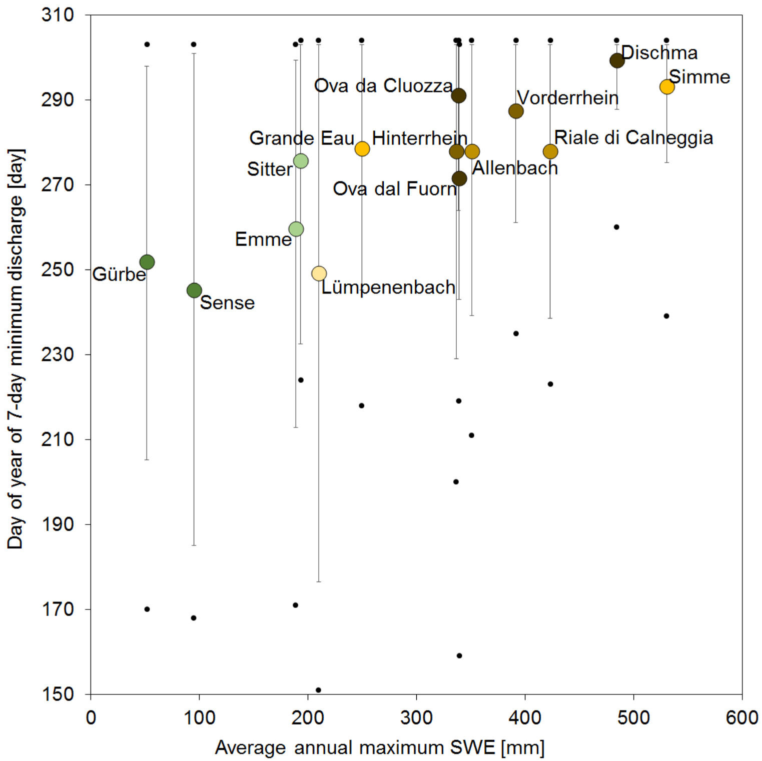


**Figure 6.** Day of year with 7 day minimum discharge against long-term mean annual maximum SWE. Whiskers represent 10 and 90 % error bars and small black dots represent minimum and maximum. The color of the circle indicates the mean value corresponds to catchment elevation (dark brown: highest; dark green: lowest).





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Importance of maximum snow accumulation for summer low flows in humid catchments

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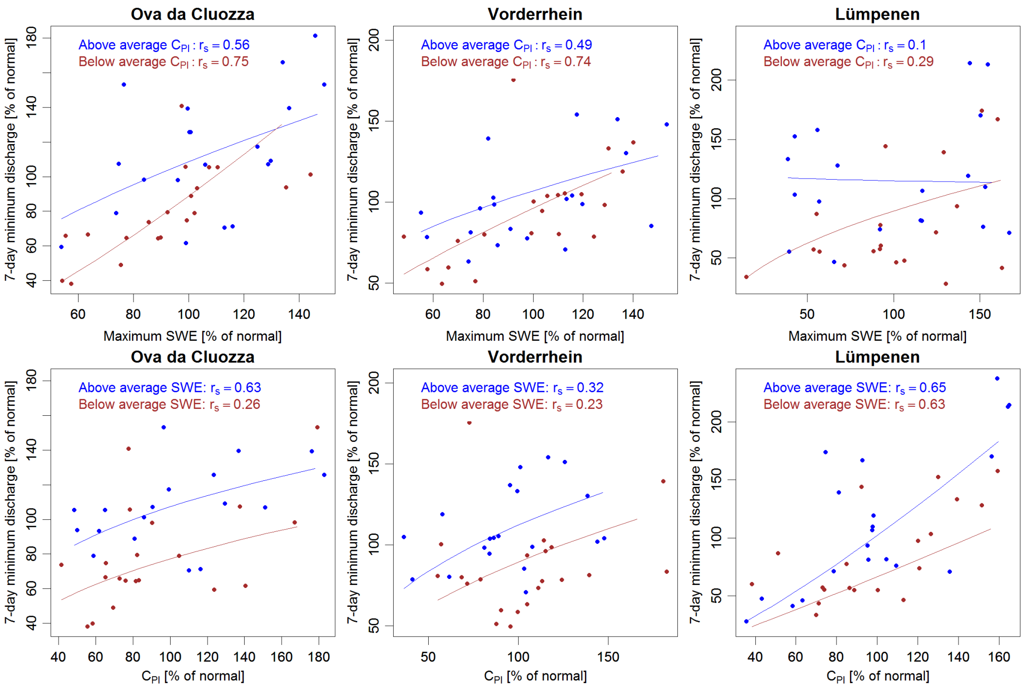


**Figure 7.** Top plots: 7 day minimum discharge in July against maximum SWE for years grouped according to the current precipitation index $C_{PI}$. Bottom plots: 7 day minimum discharge in July against current precipitation index $C_{PI}$ for years grouped according to maximum SWE. In both cases blue color indicates years with above average values and red color indicates years with below average values.

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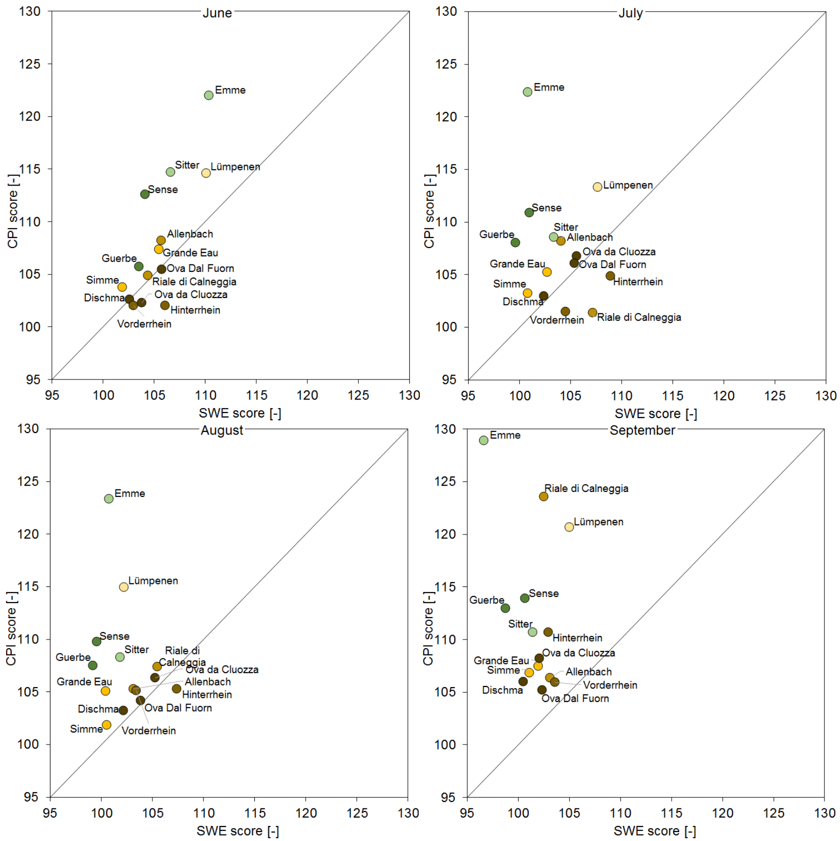


**Figure 8.** Score plots indicating the combined effect of snow and liquid precipitation on low flows in the different months (four plots for June to September). Points below the one-to-one line indicate catchments with a stronger effect of SWE on low flows compared to spring and summer precipitation (expressed as $C_{\text{PI}}$) and vice versa. The color of the symbols indicates catchment elevation (dark brown: highest; dark green: lowest).



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