Effects of climate anomalies on low flows in Switzerland

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Short summary: Low river flows affect societies and ecosystems. Here we study how precipitation and potential evapotranspiration shape annual warm season low flows across a network of 380 Swiss catchments. Low flows in these rivers typically result from below-average precipitation and above-average potential evapotranspiration. The lowest low flows result from long periods of the combined effects of both drivers.

Abstract. Large parts of Europe have faced extended periods of low river flows in recent summers (2003, 2011, 2015, and 2018), with major economic and environmental consequences. Understanding the origins of events like these is important for water resources management. While precipitation and potential evapotranspiration obviously impact summer low flows, it remains largely unquantified which characteristics of precipitation and potential evapotranspiration are related to low-flow magnitude, and how these relationships may vary regionally. To reveal how weather drives low flows, we explore how deviations from mean seasonal climate conditions (i.e., climate anomalies) of precipitation and potential evapotranspiration shaped the occurrence and magnitude of the annual 7-day lowest flows (Q_{min}) across 380 Swiss catchments from 2000 through 2018. Most annual low flows followed periods of below-average precipitation and above-average potential evapotranspiration, and the lowest low flows resulted from both of these drivers acting together. In the driest years, low-flow conditions occurred simultaneously across large parts of Europe, but low-flow timing during these years was still spatially variable across Switzerland. Low flows in the years 2003, 2011, 2015, and 2018 were associated with much longer-lasting climate anomalies compared to the maximum two-month anomalies which caused typical low flows in other years. Across Switzerland, we found that precipitation totals in winter and snow water equivalent only slightly influenced the magnitude and timing of summer and autumn low flows. Our results provide insight into how precipitation and potential evapotranspiration jointly shape low flows across Switzerland, and potentially aid in assessing low-flow risks in similar mountain regions using seasonal weather forecasts.

1. Introduction

In recent decades, Europe has experienced several severe low-flow events (Van Lanen et al., 2016). Their impacts, such as dry river reaches and high water temperatures, have a range of adverse effects on society and river ecology (e.g., Poff et al., 1997; Bradford & Heinonen, 2008; Rolls et al., 2012; van Vliet et al., 2012). Severe low flows in the years 2003, 2011, 2015 and 2018 led to substantial economic losses by limiting water availability for households, industry, irrigation and hydropower, as well as impacting river transportation (Stahl et al., 2016; Munich Re, 2019). Such effects are expected to become more severe and frequent as water demand rises, and as droughts are anticipated to increase in frequency and intensity in the future (e.g., De Stefano et al., 2012; Wada et al., 2013), leading to calls for improved understanding and management of low flows across Europe (e.g., Seneviratne et al., 2012a; Van Lanen et al., 2016; WMO, 2008).

In temperate climates, annual low flows typically occur in two distinct seasons, i.e., in late summer and autumn and in colder regions during winter (Fiala et al., 2010; Smakhtin, 2001). This typical low-flow seasonality has been reported for many regions of the world, including, for example, Austria (Laaha & Blöschl, 2006; Van Loon & Laaha, 2015), the Rhine river basin (Demirel et al., 2013; Tongal et al., 2013), and North America (Cooper et al., 2018; Dierauer et al., 2018; Wang, 2019). Switzerland also has two distinct low-flow seasons, where the distinction between warm-season low flows and winter low flows is strongly connected to elevation (Wehren et al., 2010; Weingartner & Aschwanden, 1992). Low flows in low-elevation Swiss catchments tend to occur in late summer and early autumn (August through October), whereas in high-elevation catchments most low flows occur during winter (January through March).

Catchment properties shape low flows by controlling the storage and release of water (Stoelzle et al., 2014; Van Lanen et al., 2013; Van Loon & Laaha, 2015), but the landscape itself does not cause low flows. Instead, the drivers of low flows are meteorological conditions that dry out catchments (e.g., Fleig et al., 2006; Haslinger et al., 2014 ; Smakhtin, 2001). Two distinct low-flow seasons exist throughout Switzerland (and many other regions), suggesting that different weather conditions drive low flows during these two seasons: warm-season low flows are typically caused by sustained periods of high evapotranspiration and low precipitation, whereas winter low flows often follow sustained periods of sub-freezing temperatures (e.g.; Laaha et al., 2013), Van Loon, 2015). Thus, low flows are not created instantaneously, but result from weather conditions acting over longer periods. The annual lowest flow is (for a particular year) an exceptional flow condition, so we expect low flows to occur after weather conditions that are atypical (for that same year). From now on, we refer to atypical weather conditions as 'climate anomalies'.

The two main climatic factors controlling water storage and release in a catchment are precipitation and temperature (through controlling snow processes and evapotranspiration). It is therefore likely that precipitation and potential evapotranspiration (PET) anomalies are important drivers of warm-season low flows across Switzerland. For example, precipitation controls the amount of water that is made available to a catchment. Sustained periods with little precipitation will inevitably reduce storage and thereby limit streamflow. Because there is a time lag between low precipitation and low streamflow, meteorological droughts (i.e., precipitation deficits) result in hydrological droughts and/or low flows if they persist for long enough (Peters et al., 2006; Tallaksen & Van Lanen, 2004; Van Loon, 2015). In Switzerland, there is limited precipitation seasonality, but precipitation can still vary substantially within seasons or from year to year. However, in coming decades, precipitation is expected to become increasingly seasonal with changing climatic conditions, with less precipitation during summer and more precipitation in winter (CH2018, 2018).

High temperatures (or high PET) can deplete soil moisture storage, thereby reducing aquifer recharge and streamflow (Jaeger & Seneviratne, 2011; Vidal et al., 2010). This effect is amplified when low soil moisture limits evapotranspiration, leading to lower relative humidity and higher air temperatures, which further increase PET. Furthermore, vegetation decreases the amount of water available for streamflow by increasing evaporative water use during periods of high water-vapor deficits. Although these mechanisms are known, the effects of evapotranspiration on low-flow occurrences and magnitudes have received relatively little attention compared to precipitation effects. Seneviratne et al. (2012) reported that low flows of 2003 across Switzerland were most likely more the result of evapotranspiration excess rather than spring precipitation deficits, and Teuling et al. (2013) have documented the depletion of soil water storage by high evapotranspiration during past European low flows. Woodhouse et al. (2016) reported that temperatures rather than precipitation explained the interannual streamflow variations of the Colorado river. More recently Cooper et al. (2018) reported that summer low flows in the maritime Western US are largely driven by summer PET, rather than by winter precipitation or snow water equivalent. Mastrotheodoros et al. (2020) modeled how increasing evapotranspiration strongly reduced streamflow across the European Alps during the summer of 2003. Future PET is projected to increase along with increases in incoming longwave radiation (Roderick et al., 2014), with uncertain consequences for future low flows. In Switzerland, in the next decades, temperatures are expected to rise even quicker than the global average (CH2018, 2018), potentially influencing low-flow dynamics.

Future climate changes will also affect low flows in mountain regions by altering snowpack accumulation and meltwater release. Multiple studies have examined how winter precipitation and snow water equivalent affect summer low flows. For example, Godsey et al. (2014) found that decreasing snowpacks in the Sierra Nevada of California led to smaller low flows in the following summers. Jenicek et al. (2016) reported that maximum snow accumulation strongly affected summer low flows across several Swiss catchments. Dierauer et al. (2018) found that warmer winters with less snow accumulation led to lower summer low flows in mountainous catchments of the Western United States. Recently, Wang (2019) reported that climate warming might increase aquifer conductivity and thereby streamflow in cold region watersheds. Future climate warming in both warm and cold seasons will most likely impact summer low flows through different mechanisms. In summer, higher temperatures increase potential evapotranspiration, whereas in winter they reduce snowpacks (e.g., Déry et al., 2009; Diffenbaugh et al., 2015; Musselman et al., 2017). The effects of precipitation, temperature and evapotranspiration on low flows have been investigated for individual events or individual catchments and regions. Previous studies have largely focused on how signatures of low flows (averaged across many events) relate to catchment and climate characteristics (e.g., Fangmann & Haberlandt, 2019; Hannaford, 2015; Laaha & Blöschl, 2006; Van Loon & Laaha, 2015). So far, few studies have systematically assessed the direct impact of temperature and precipitation during periods immediately preceding individual annual low-flow events across many catchments in a topographically diverse region.

Here we explore how precipitation and PET deviations from their seasonal norms (here termed "climate anomalies") jointly shape the occurrence and magnitude of annual warm-season low flows across a network of 380 Swiss catchments. Because low flows are normally atypical flow conditions, we expect them to follow atypical weather conditions, rather than reflecting climate seasonality alone. Therefore, we hypothesize that low flows will typically occur after anomalous weather conditions, that is, weather conditions that deviate substantially from the seasonal norm. Understanding how anomalous weather drives low flows may help to reveal the processes at work, and also may support low-flow forecasting. Switzerland is an interesting study region because gauging and climate data are available from a dense station network spanning a wide range of elevations, climates, and topographies. We investigate (a) how precipitation and PET anomalies separately and jointly shape the occurrence and magnitude of low flows across Switzerland, (b) which durations of these anomalies have the strongest impact on low-flow occurrence and magnitude, both in typical and in exceptionally dry years, and (c) how winter precipitation and snow packs influence the magnitude and timing of summer low flows. Understanding these connections is important for anticipating how streamflows are likely to respond as the exceptionally dry years of today are expected to become more typical in a future warmer climate.

2. Data and methodology

2.1. Streamflow and climate data

We compiled daily streamflows for 380 gauging stations across Switzerland for a 19-year period (2000-2018), using data collected by the Swiss Federal Office of the Environment (FOEN) and the Swiss Cantonal authorities. Low flows were defined as the lowest 7-day average streamflow for each year (Q_{min}). We determined the catchment area and the mean catchment elevation for each gauging station based on a 2-m DEM (SwissAlti3D 2016, Swisstopo), using functions provided in the ArcGIS "Spatial Analyst" toolbox. The catchments range in size from 1 to 519 km^2, vary in mean elevation from 309 to 2930 m, and are distributed across different regions with diverse landcovers and climates. Daily gridded precipitation and temperature data (~2x2 km cells; Meteoswiss products "RhiresD" and "TabsD") were used to derive catchment-averaged weather and climate conditions. Daily potential evapotranspiration (PET) was estimated following the method of Hargreaves & Samani (1985). A gridded dataset of snow water equivalent (SWE) on March 1st of each year was used to estimate catchment-average SWE. The SWE product was based on data from 320 Swiss snow monitoring stations that were assimilated into a distributed snow cover model (Magnusson et al., 2014; Griessinger et al., 2016).

2.2. Anomalies of climate variables

To infer which climate conditions cause annual low flows, we selected the annual 7-day minimum streamflow events (Q_{min}) in each catchment for each year from 2000 to 2018. There were years when the lowest annual flows were much higher than typical low flows. We removed outliers by the 3-sigma rule, a standard procedure in statistics to remove extreme tails of a distribution (Pukelsheim, 1994). The removal of unusually high annual low flows that exceeded three standard deviations above the catchment mean of all annual low flows resulted in the removal of 2% of all low flows. We then calculated precipitation and potential evapotranspiration for time windows of different lengths prior to each annual low flow. We hypothesize that severe low flows will usually follow periods in which precipitation and potential evapotranspiration significantly deviate from their seasonal norms (i.e., the average conditions during that time of the year). Thus, we define climate anomalies as deviations of precipitation and potential evapotranspiration from their climatic norms, defined as their long-term averages on the same day of the year. For example, we quantify precipitation anomalies (in mm) by:

$$\sum_{t=d_l-d_t}^{d_l} P(t) - \bar{P}(t) \qquad Eq.(1)$$

where $P(t)$ is daily precipitation (mm) at day t, $\bar{P}(t)$ is the climatic mean precipitation on day t averaged across all of the years of record, d_t is the time period over which anomalies are calculated for each annual low flow, and d_l is the day of the low flow. We vary the time period d_t from one week to half a year (7, 14, 30, 60, 90, 120, 182 days), with the endpoint always being the date of the low flow. For example, the 30-day precipitation anomaly for a low flow that happened on 30 September 2018 is calculated using the sum of precipitation from 1st to 30st September 2018 minus the mean of precipitation for all 1st to 30st September periods from 2000 to 2018. We calculate PET anomalies in an equivalent manner.

2.3. Statistical tests and quantification of process importance

Because relations between the climate anomalies and annual low-flow characteristics can be non-linear, we use Spearman rank correlation coefficients (r_S) to quantify their dependence (Legates & McCabe, 1999). The statistical significance of the distributions of r_S across the study catchments is assessed with the sign test, indicating if a distribution is significantly positive or negative. To quantify the individual and joint importance of precipitation and PET anomalies we first calculated the bivariate Spearman rank correlation between the individual anomalies and Q_{min} for the different time windows (30, 60, 90, 120, 182 days) for all years (2000-2018) and for the years with the lowest low flows (2003, 2011, 2015 and 2018). For this analysis we reduced the original dataset to only selected warm-season low flows in May through November and those catchments where at least 5 years of Q_{min} data were available, and calculated correlations for all years and the years with the lowest low flows (2003, 2011, 2015 and 2018). In a next step we used the joint anomalies of precipitation and PET for the durations 30, 60, 90, 120, 182 days to predict Q_{min} with a multivariate stepwise generalized linear model (GLM). We then computed the fraction of the maximum R^2 achievable by the joint GLM by the individual precipitation and PET anomalies for each duration, to assess which of the anomalies is a better predictor. We compare the results for all years to those for the lowest-flow years (2003, 2011, 2015 & 2018) to assess if different mechanisms are at play during the driest years.

3. Results and Discussion

3.1. Climate anomalies control low-flow timing and magnitude

The occurrence of low flows is linked to periods of below-average precipitation and above-average PET (Fig. 1a&b). However, distinct site-to-site differences exist: at elevations below approximately 1500 m asl, almost all annual low flows occur after periods of anomalously high potential evapotranspiration and anomalously low precipitation (Fig. 1a&b). At higher elevations, by contrast, PET anomalies have no systematic effect and precipitation anomalies become less important with increasing elevation. This reduced importance of anomalies at these higher elevations is probably because low flows here result primarily from freezing temperatures (or periods of snow accumulation), rather than precipitation or PET patterns. Low flows at higher elevations occur during the winter months when there is a lack of liquid water inputs to catchments, due to precipitation mostly accumulating as snow, with little snowmelt. These processes are mainly driven by sustained below-zero temperatures. Thus, the main determining factor in winter low flows at high elevations (or in cold environments) will likely be the length of the snow accumulation period, rather than what the exact temperatures were, or how much precipitation occurred.

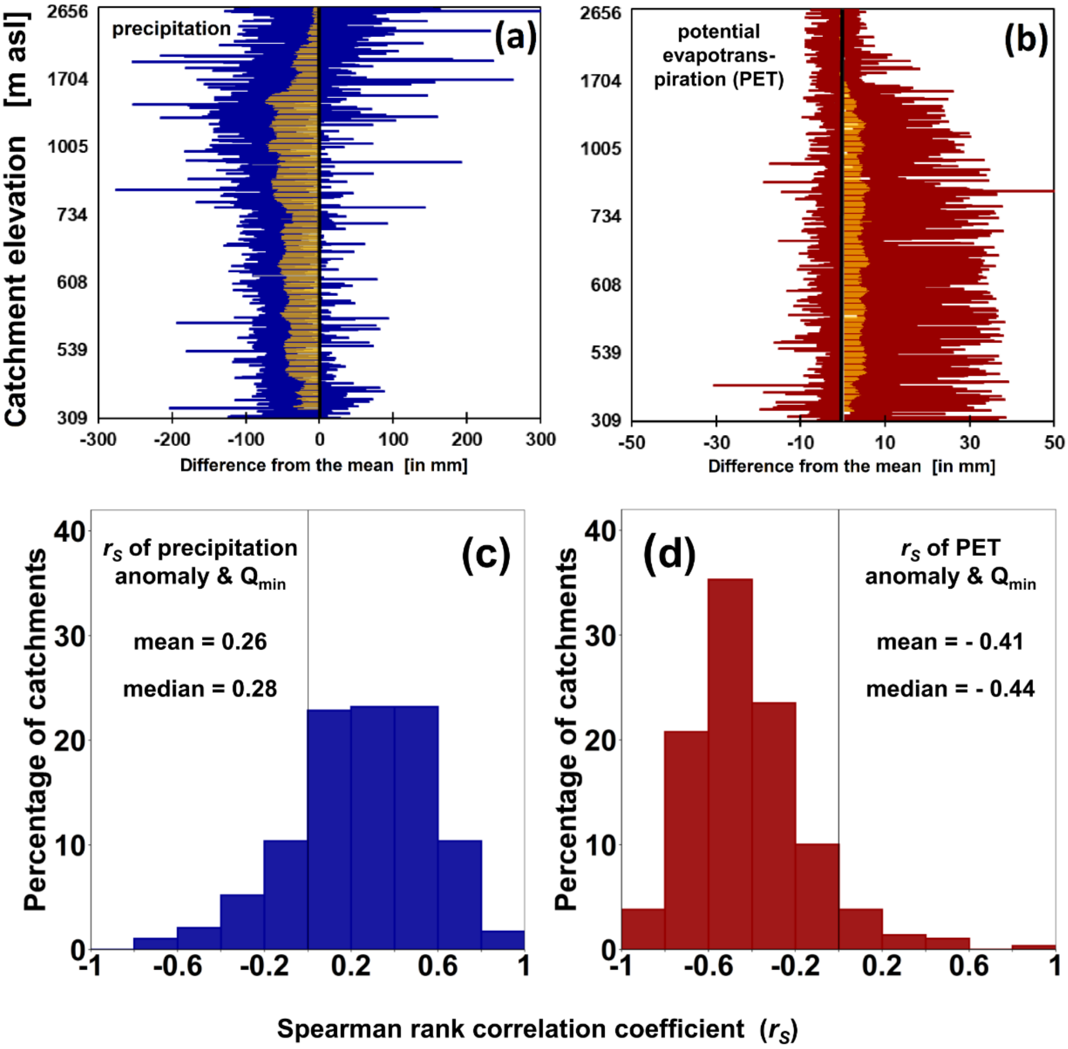

Figure 1: Altitudinal variation in 30-day anomalies of precipitation (a) and potential evapotranspiration (b) preceding annual low flows from 2000 through 2018. Blue and red horizontal bars indicate the range between the minima and maxima of these anomalies at each catchment across the 19 years of this study. Yellow bars show moving averages of these climate anomalies for bins of 10 catchments ordered by elevation. Note that the elevation scale is not linear. Low flows are associated with below-average precipitation (a) and above-average potential evapotranspiration (b); however, above roughly 1500 m asl, PET anomalies have no systematic effect and precipitation anomalies become less important with increasing altitude. Histograms of rank correlations between anomalies of precipitation (c) and potential evapotranspiration (d) and low-flow magnitudes for late summer and autumn (May through November) low flows across Swiss catchments. Low-flow magnitudes tend to be positively correlated with precipitation anomalies and negatively correlated with PET anomalies, but with considerable site-to-site variability.

More severe climate anomalies tend to lead to lower low flows (Fig. 1c&d). Spearman rank correlations of magnitudes of the climate anomalies to magnitudes of Q_{min} (shown for the months May through November) indicate that lower precipitation in the 30 days prior to Q_{min} usually results in smaller Q_{min} (median r_S=0.28). Similarly, higher potential evapotranspiration usually results in smaller Q_{min} (median r_S=-0.44). This indicates that the magnitudes of both precipitation and PET anomalies tend to affect low-flow magnitudes (p-values < 0.001 according to the sign test), but with substantial site-to-site variability.

3.2. Combined effects of climate anomalies on low flows

Our previous results (Fig. 1) indicate that both precipitation and PET can affect low flows. However, most low flows are not caused by only one driver, but instead result from the combined effects of below-average precipitation and above-average PET both acting at the same time. Warm-season low flows, occurring from May through November, usually follow periods of below-average precipitation and above-average potential evapotranspiration (72.2% of low flows fall in the top left quadrant of Fig. 2a). Less than a quarter of the annual low flows occur after periods of below-average precipitation and below-average potential evapotranspiration (20.5% lower left quadrant – Fig. 2a). Only very few annual low flows (7.3%) occur after periods of above-average precipitation. Thus, precipitation anomalies appear to be the most important driver for warm-season low flows in Switzerland, and potentially also in other regions with distinct warm-season low flows. While potential evapotranspiration appears to be less important than precipitation, more than 70% of low flows are caused by a combination of both drivers. The combined effect of above-average PET thus more than triples the chance of an annual low flow (compared to when precipitation is below average, but there is below-average PET).

Particularly severe low flows occur through the combined effects of low precipitation and high potential evapotranspiration. For example, 96% of low flows during the most severe low-flow year (2003, shown by green markers in Fig. 2a) follow periods of both below-average precipitation and above-average potential evapotranspiration. This behavior is not unique to the 2003 event, but was also observed for other years with severe annual low flows such as 2011, 2015 and 2018 (Fig. 2b&c).

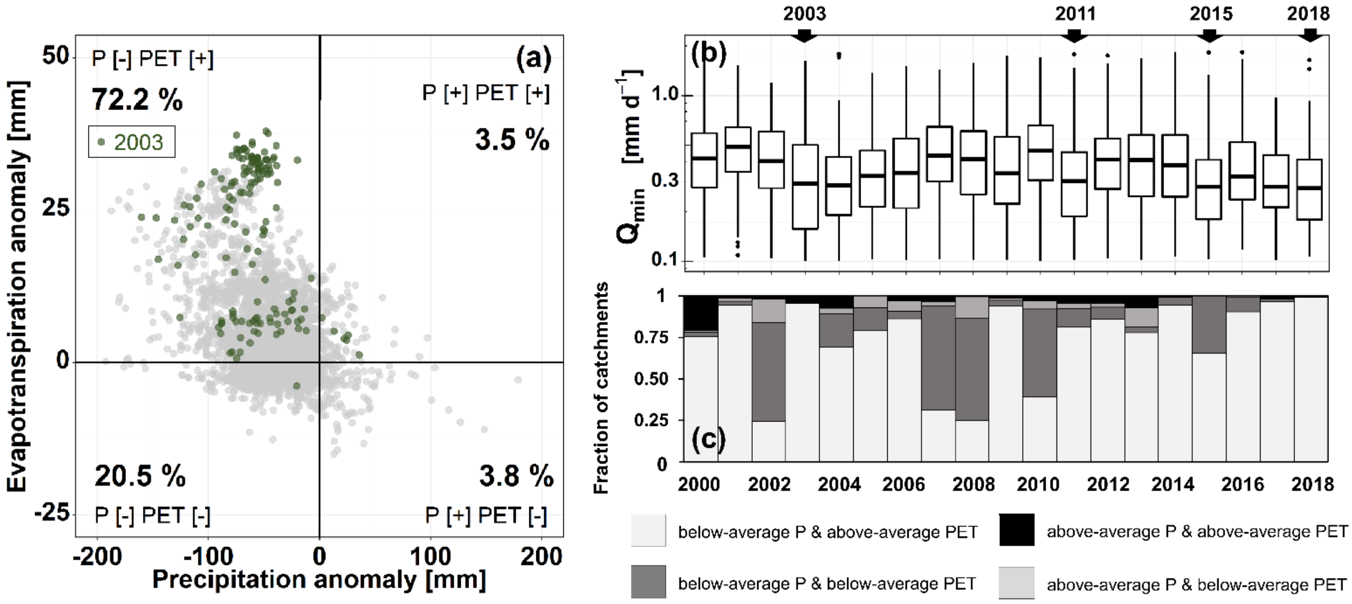

Figure 2: Anomalies in precipitation and potential evapotranspiration 30 days prior to each annual late-summer and autumn (May through November) low-flow period in each catchment (grey dots); winter low flows were excluded (a). The most severe low-flow year during the study (2003) is highlighted in green. Almost all (92.7%) annual low flows occurred following below-average precipitation (the left half of the figure), and 72.2% of all low flows occurred following a combination of below-average precipitation and above-average potential evapotranspiration (the upper left quadrant of the figure). Boxplots of annual 7-day minimum flows in May through November for the Swiss study catchments (b) and the catchment distribution of the signs of precipitation and evapotranspiration anomalies that preceded these low flows (c). The most severe low-flow years (2003, 2011, 2015, and 2018) were characterized by negative precipitation anomalies and positive *PET* anomalies for the large majority of catchments, as indicated by the

light grey bars in (c). The horizontal line of the boxplots indicates the median, the box represents the interquartile range and the whiskers extend to 1.5 times the interquartile range above and below the box; the dots are outliers.

During the dry years of 2003, 2011, 2015, and 2018, low-flow conditions occurred across large parts of Europe (Laaha et al., 2017; Van Lanen et al., 2016). Annual low flows did not occur simultaneously across Switzerland, but instead occurred primarily during winter in the Alpine regions and summer and autumn in the Swiss Plateau (Fig. 3). In addition, within these two sub-regions, the timing of low flows was still spatially variable, indicating that annual low flows may be surprisingly asynchronous across Switzerland even in extremely dry years, when the climate drivers are similar (Fig.2c). Within the Swiss Plateau, low-flow timing is more spatially consistent during some years without severe low flows (e.g., 2009, 2013, 2016), than during others (e.g., 2000, 2002, 2004, 2010, 2017).

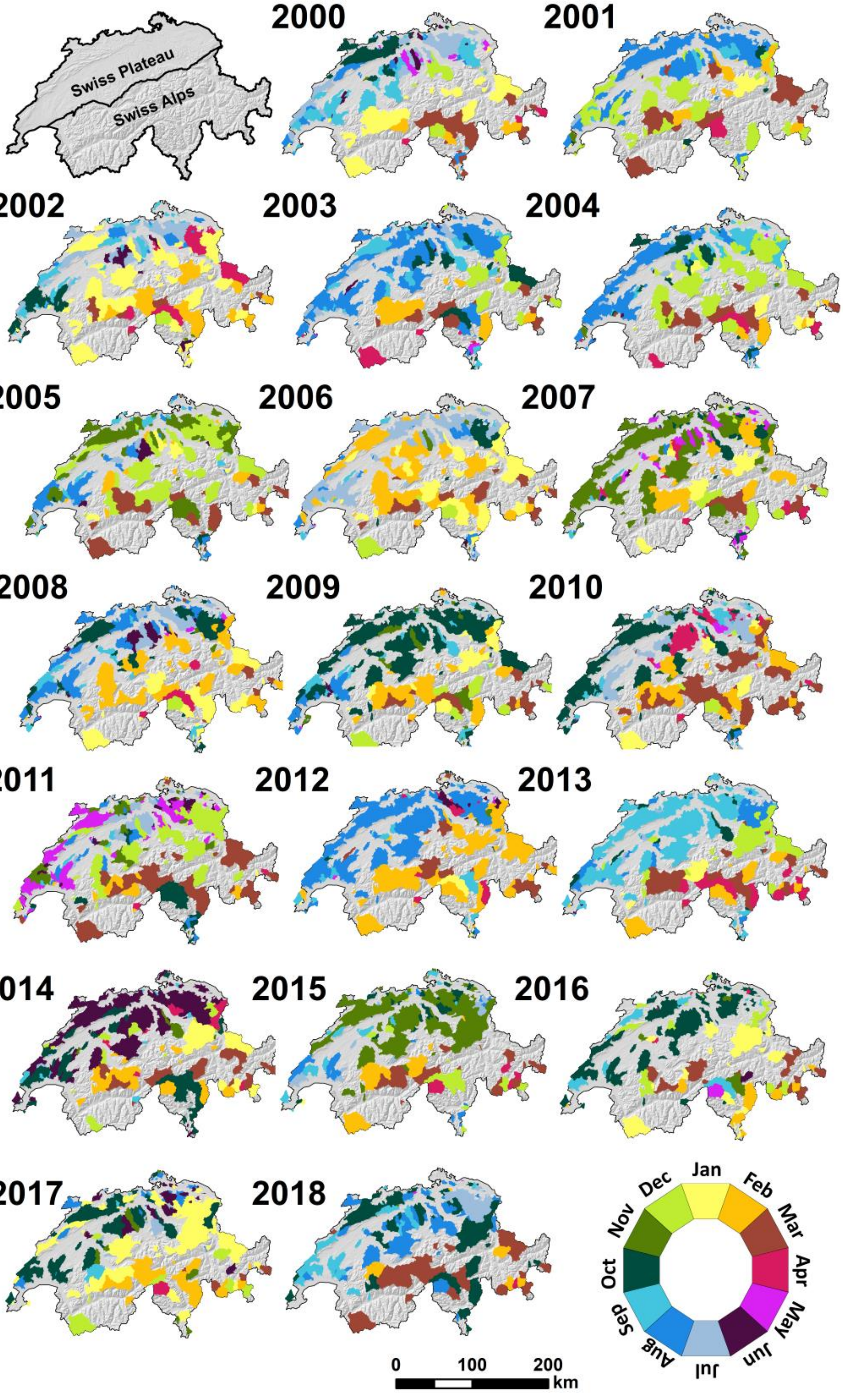

Figure 3: The timing of occurrence of annual low flows across Switzerland for the years 2000 to 2018 in the two main regions: the Swiss Plateau and Swiss Alps (roughly the northern and southern halves of the country, respectively). Low-flow timing tended to be spatially heterogeneous, even in years when large parts of Europe simultaneously experienced severe low flows (2003, 2011, 2015, 2018).

3.3. Duration of climate anomalies

The magnitudes of low flows are also related to the durations of the preceding precipitation and evapotranspiration anomalies. Longer periods of below-threshold precipitation and above-threshold PET tend to lead to lower low flows in most of our catchments (Fig. 4). The duration of high PET is more strongly correlated with low-flow magnitudes than the duration of low precipitation is (mean Spearman correlations r_S of -0.27 and -0.11 respectively; medians differ from 0 at $p<0.001$ by sign test; Fig. 4). The weaker correlation with the duration of below-threshold precipitation probably arises because precipitation is more erratic than PET. A single precipitation event may exceed the precipitation threshold (according to the criteria outlined in the caption to Fig. 4), but not nearly enough to end the low flow in the stream. Low-flow magnitudes are less strongly correlated with the duration of below-threshold precipitation than with the intensity of 30-day precipitation anomalies (compare Fig. 4 with Fig. 1; mean r_S of -0.11 and 0.26, respectively). Similarly, low-flow magnitudes are less strongly correlated with the duration of above-threshold PET than with the intensity of 30-day PET anomalies (compare Fig. 4 with Fig. 1; mean r_S of -0.27 and -0.41, respectively).

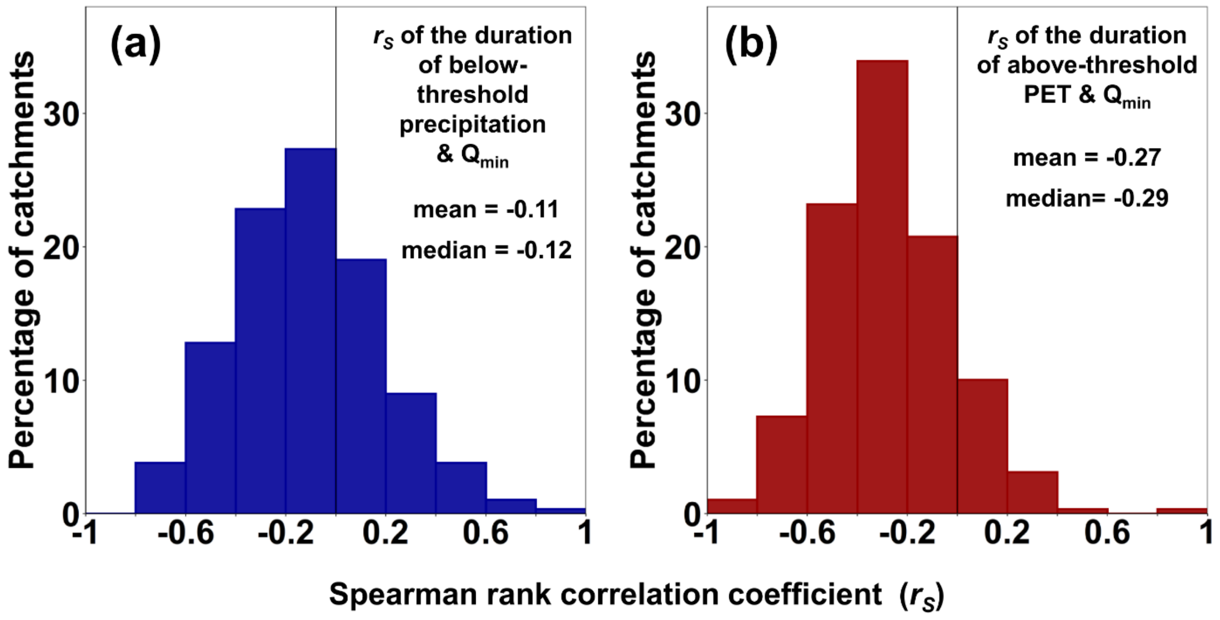

Figure 4: Histograms of rank correlations between the magnitudes of late summer and autumn (May through November) low flows and the lengths of the preceding intervals with low precipitation (a) or high PET (b). The threshold that defines low precipitation is the 20^th^ percentile of the 10-day running averages of precipitation over the entire period of record. Similarly, the threshold that defines high PET is the 80^th^ percentile of the 10-day running averages of PET over the entire period of record. Histograms show distributions of rank correlations calculated for each catchment based on the 19 years of data. Longer periods of high PET are associated with lower low flows, whereas a weaker association is seen between lower flows and longer periods with low precipitation.

Summing precipitation and PET anomalies over time windows ranging from one week to half a year indicates that most low flows can be well explained by anomalies of up to 60 days (Fig. 5). This is because in the typical Swiss climate, precipitation and PET anomalies usually last for 60 days or less. This is depicted by the grey cloud of points in Fig. 5, as well as the mean anomalies (indicated by the dotted lines in Figs. 5a-g) which remain approximately stable for periods exceeding 60 days. Thus, while longer precipitation and PET anomalies would lead to lower flows, most low flows result from anomalies of up to 60 days. This is because most anomalies peak at around that 60-day time scale, which is also indicated by the mean of precipitation and PET anomalies as a function of timescale (dashed line in Figs. 5h and 5i).

The severe low flows in 2003, 2011, 2015 and 2018, however, are associated with precipitation and PET anomalies that grow for much longer, and thus become much larger, than the roughly 60-day anomalies that are typical in this climate (colored symbols in Fig. 5). Long periods of above-average PET appear to be an important factor for these severe low flows; the colored points in Figs. 5e-g expand more on the y-axis than the x-axis for timescales >60 days. Thus, severe low flows result from longer-lasting (and thus larger) precipitation and PET anomalies, whereas more typical low flows result from climate anomalies that end after roughly 60 days, as illustrated by Figs. 5h&i.

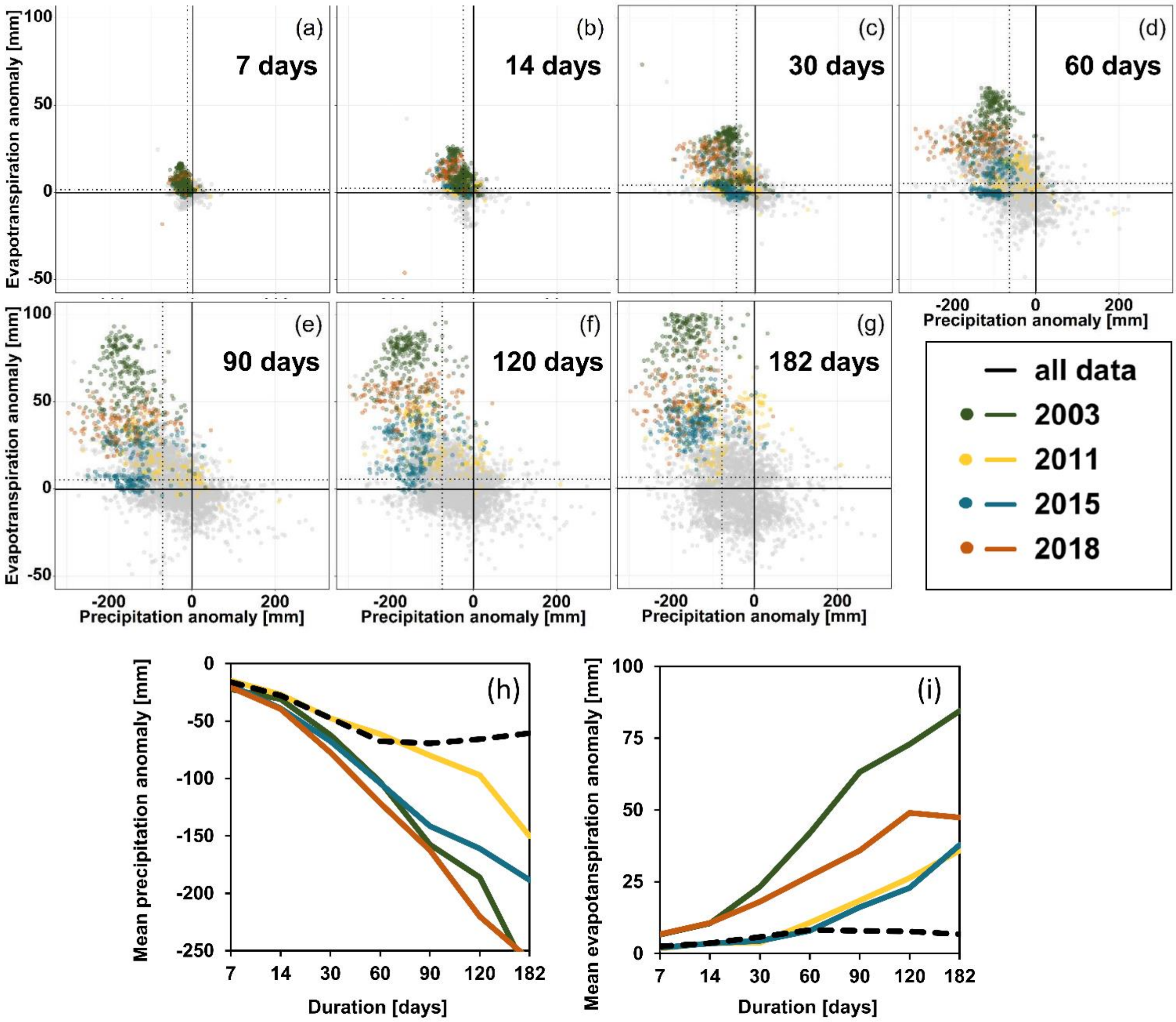

Figure 5: Cumulative anomalies of precipitation and potential evapotranspiration over 7, 14, 30, 60, 90, 120 and 182 days prior to every annual late summer and autumn (May through November) low flow in each catchment (a-g), and the evolution of the mean anomalies over the different time windows (h & i). Each grey dot represents the combination of precipitation and PET anomalies before one low-flow event at one site. Low-flow anomalies in the most severe low-flow years are indicated by different colors (2003 in green, 2011 in yellow, 2015 in cyan and 2018 in orange). The

dotted lines indicate the mean precipitation and PET anomalies. The mean anomalies (dotted lines in all panels) exhibit clear growth within the first 60 days prior to low flows, but show no clear trend over longer time windows. During the most severe low-flow years, however, the mean anomalies continue to increase across all of the time windows examined here. In particular, the PET anomalies during the severe low-flow years grow well beyond the range that is observed during more typical years.

3.4.The relative importance of P and PET anomalies on low-flow magnitudes

We further assessed the relative importance of each of the climate drivers and their duration in predicting the magnitude of annual low flows by calculating the bivariate Spearman rank correlation between each climate driver and Q_{min} as one value for all stations and years together (Fig. 6). The results also include the site-to-site variability in Q_{min}, thus the overall r_S correlations are weaker than those shown in Fig. 1c&d. Typical low flows across all years of the observation period (2000-2018) are more strongly correlated to precipitation anomalies than to PET anomalies (see also Fig. 1), and this correlation becomes stronger at longer durations. However, during the driest years of our dataset (2003, 2011, 2015 and 2018), the correlation between precipitation anomalies and Q_{min} drops to roughly zero, suggesting that under these extreme conditions low precipitation alone cannot explain the variation in annual low-flow magnitudes. Instead, in these dry years PET anomalies retain their predictive power for Q_{min}, suggesting a relatively more important role of PET in these years.

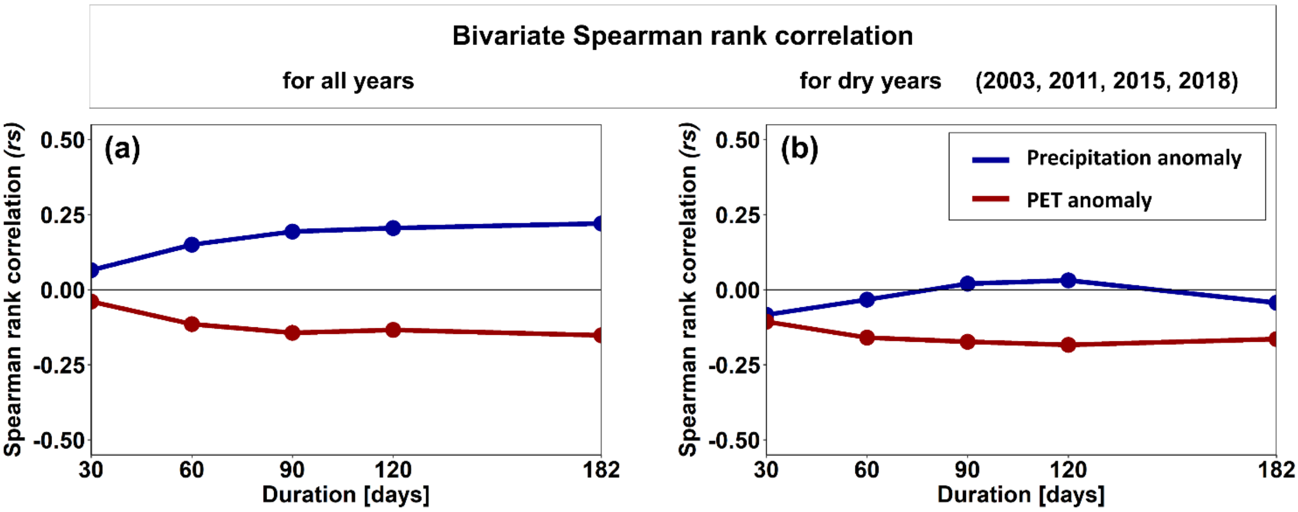

Figure 6: Bivariate Spearman rank correlation coefficients between precipitation (blue) and PET anomalies (red) and Q_{min} of warm season (May to November) low flows for durations of 30, 60, 90, 120 and 182 days, across all stations and years. The overall explanatory power of the climate anomalies in a bivariate regression framework is low, although precipitation anomalies are slightly better correlated to Q_{min} than PET anomalies in the whole dataset (a). In the four driest years (b) the overall explanatory power of precipitation anomalies is much smaller, whereas the explanatory power of PET anomalies is slightly greater than for all years.

To quantify how much of the maximum predictive power lies in individual anomalies, we first used a multivariate stepwise generalized linear model (GLM) to predict Q_{min} as a function of all precipitation and PET anomalies for durations of 30, 60, 90, 120 and 182 days. In Fig. 7 we show the fraction of the R^2 explained by this model with individual P and PET anomalies for the different durations. Across all stations and years of the observation period (2000-2018), warm season Q_{min} is best predicted by precipitation anomalies with increasing duration (Fig. 7a), which shows the cumulative effect of low precipitation.

However, in the years with the lowest annual warm season low flows (2003, 2011, 2015 and 2018) the picture reverses, and instead PET explains most of the predictability in Q_{min} up to about 50% of the best predictive GLM model. This is true across a wider range of durations, starting even at 30 days. Thus, although precipitation anomalies are a good predictor for typical low flows, low flow magnitudes in the driest years are more strongly related to PET anomalies when precipitation anyway is very low.

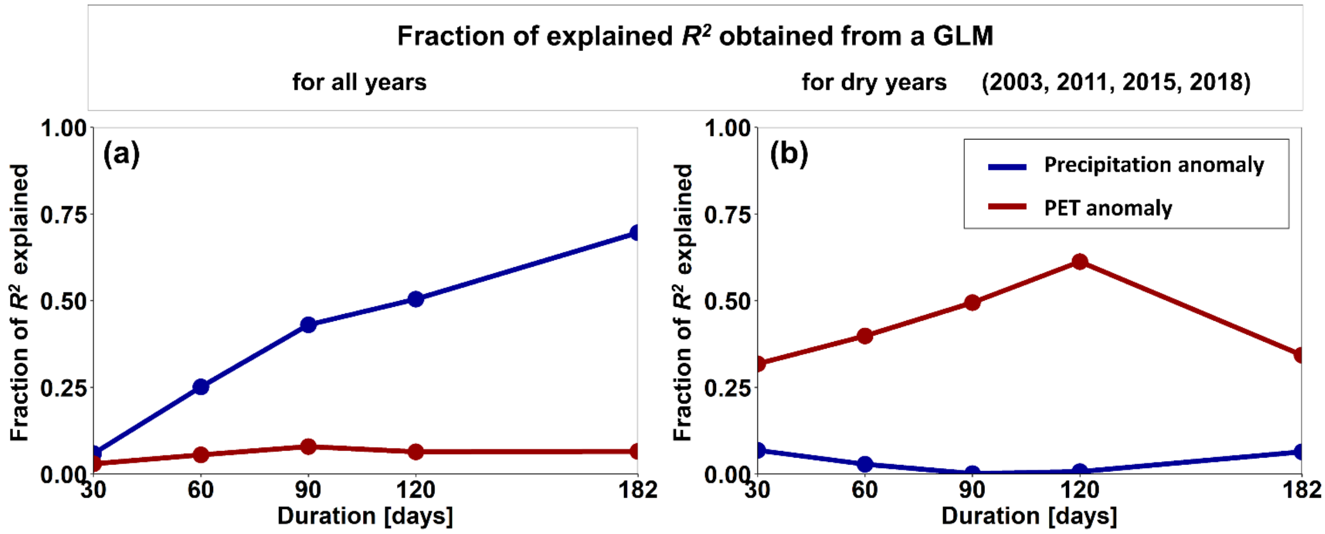

Figure 7: The fraction of multivariate R^2 - calculated by a stepwise generalized linear regression model (GLM) with all climate variables and warm season (May to November) low flows - that can be explained by a precipitation (blue) or PET (red) anomaly of a certain duration. Precipitation anomalies explain most of the variation in Q_{min} when looking at all stations and all years (a). However, precipitation anomalies are not good predictors for low flows that occurred in the driest years (2003, 2011, 2015, 2018) and instead PET anomalies are much better predictors of Q_{min} (b).

3.5. The influence of winter precipitation and snow on summer low flows

Previous studies indicate that winter snowpack and snowfall can influence the timing and magnitude of summer low flows (e.g., Dierauer et al., 2018; Jenicek et al., 2016; Godsey et al., 2014). If this holds true for our study catchments, more winter precipitation (December through March), or higher SWE on March 1st, should lead to larger and later summer/autumn low flows. To test for this effect, we calculated Spearman rank correlations between winter precipitation totals and subsequent low-flow magnitudes and timing (May through November). The correlations between winter precipitation and the magnitude and timing of Q_{min} (mean absolute $r_S < 0.11$ for both; grey bars in Fig. 8) are weaker than those between low-flow magnitudes and climate anomalies in the period directly before the low flow (Figs. 1c&d), and they do not vary systematically with altitude. We also calculated the Spearman rank correlations between SWE on March 1st of every year and subsequent low-flow magnitudes and timing, and also found no strong relationship (Fig. 8, green bars; mean absolute $r_S < 0.17$ for both).

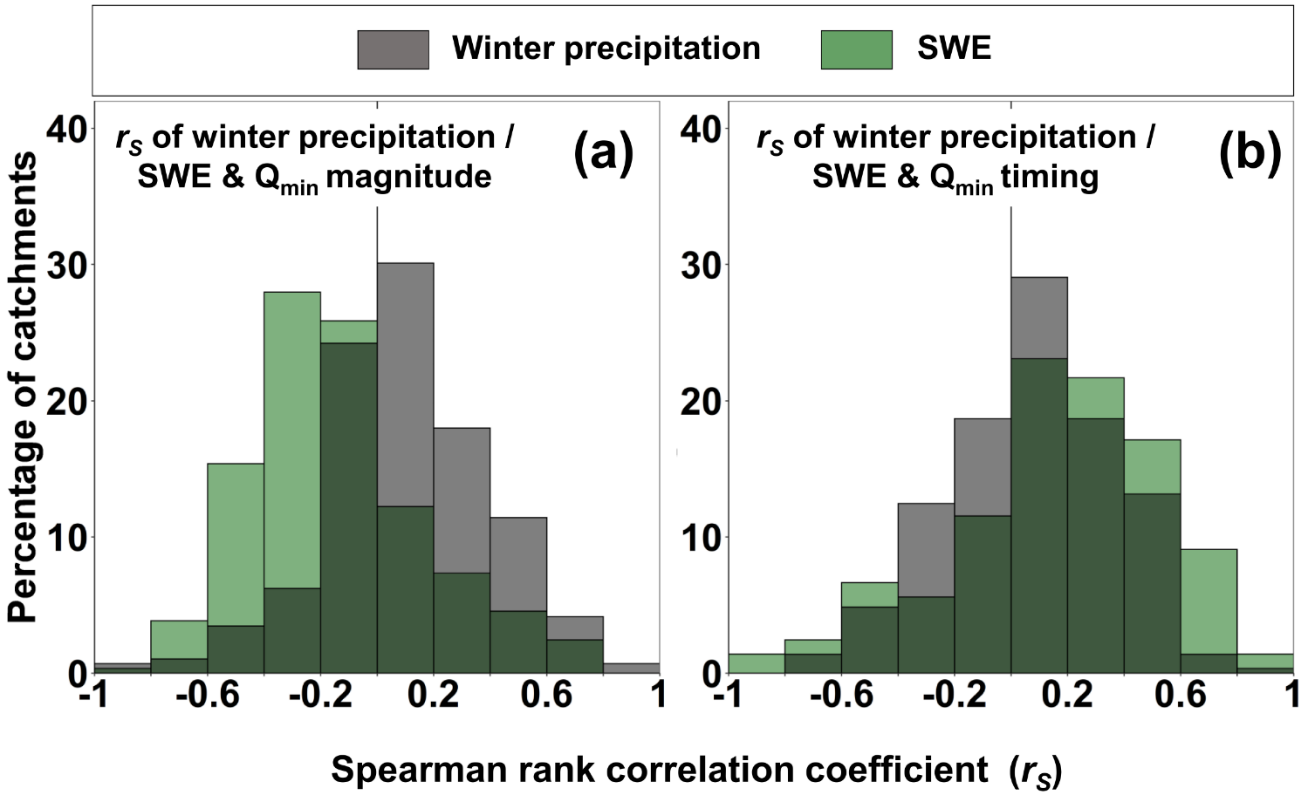

Figure 8: Histograms of the rank correlations between winter precipitation (December through March – grey bars) and snow water equivalent (SWE) on March 1st (green bars) and the magnitude (a) and timing (b) of summer low flows (May through November). Winter precipitation is weakly associated with higher, and later, low flows, as indicated by the positive r_S for the majority of catchments, however overall correlations are weak, with considerable site-to-site variability.

4. Discussion

4.1 Climate anomalies control low-flow timing and magnitude

Anomalies of precipitation and potential evapotranspiration affect the magnitude of low flows, but their influence decreases with elevation (Fig.1 a&b). This pattern is probably not unique to Switzerland, and we expect precipitation and PET anomalies to also be relatively unimportant in other cold regions where low flows primarily occur in winter (e.g., Dierauer et al., 2018; Laaha & Blöschl, 2006; Van Loon et al., 2015; Wang, 2019), driven by extended freezing periods. However, warm-season low flows are more common globally (e.g., Dettinger & Diaz, 2000; Eisner et al., 2017), suggesting that summer climate anomalies are likely to be important not only for the lower-elevation catchments in Switzerland, but also across many other regions of the world.

We found that the combined effect of P and PET anomalies shapes the occurrence and magnitude of low flows whereby the more extreme low flows are driven by longer-duration anomalies. Typical warm season low flows result from climate anomalies of up to 60 days (Fig.5). In Switzerland, typical low flows result from relatively short climate anomalies, probably because precipitation does not have a strong seasonal signature. In climates that typically have frequent precipitation events, short periods (e.g., one to two months) with less precipitation than normal will most likely lead to the annual low flow. Similarly, PET patterns are relatively comparable between years, whereby short deviations from the norm can already generate typical annual low flows. In the years with the lowest low flows (2003, 2011, 2015 and 2018), the duration of climate anomalies was significantly longer, and especially the impact of PET anomalies was larger (Figure 5). This highlights precipitation and evapotranspiration as combined drivers of severe low flows, consistent with findings in several experimental catchments during the 2003 low flow (Teuling et al., 2013). Our results suggest that the magnitude and duration of these precipitation and PET anomalies are generally important controls on severe low flows in a large, diverse sample of mesoscale catchments across Switzerland. These compound effects of PET and precipitation anomalies might also be important for low flows across larger regions (e.g., Stahl et al., 2010), as the climate conditions in Switzerland are comparable to those in other densely populated regions in the world. However, we only analyze these processes on timescales of up to half a year, so long-term memory effects in low-flow generation may not be fully captured by this approach.

The pronounced effect of PET in the years with the lowest low flows might also reflect the coupling of P and PET during dry and warm periods. Low precipitation and high air temperatures might lead to soil moisture depletion, forcing plants to reduce transpiration, resulting in lower relative humidity. These soil moisture deficits can thus lead to lower latent heat fluxes and greater sensible heat fluxes from the surface, thus increasing temperature (and thus increasing PET while reducing actual evapotranspiration). This complementary relationship between evapotranspiration and PET can amplify the apparent effect of PET during (extended) dry periods. Conversely, in locations where transpiration is not limited by water availability (e.g., at higher elevations), high temperatures and larger vapor pressure deficits (i.e., high PET) may drive increases in transpiration rates, accelerating the depletion of catchment water stores and thereby reducing runoff. For example, Mastrotheodoros et al. (2020) showed how increased evapotranspiration at higher altitudes systematically amplified runoff deficits during severe low flows in 2003 across the European Alps. These processes are especially relevant in view of potential future climatic changes. In Switzerland, climate change is expected to increase temperatures by more than the global average, resulting in warmer summers with less warm-season precipitation (CH2018, 2018). Similar trends are reported for other regions of the world. This highlights the effects of water removal through evapotranspiration, especially during extended dry periods, which are expected to become more severe with changing climate conditions.

A small fraction of all warm-season low flows in the period 2000 to 2018 followed periods of above-average precipitation and below-average PET (4% in lower right quadrant – Fig. 2a). These anomalies are expected to lead to above-average flow conditions, but can nonetheless lead to annual low flows for at least two reasons. First, these low flows occur in years that are relatively wet, with relatively high annual low flows (Fig. 3b). Second, flow conditions in most Swiss catchments are highly seasonal (Wehren et al., 2010; Weingartner & Aschwanden, 1992), meaning that the seasonality of the flow regime can in some years outweigh the effects of shorter-term weather.

4.2 The influence of winter precipitation and snow on warm-season low flows

Previous work in several Swiss catchments has suggested that the snow-water equivalent (SWE) accumulated in the winter snowpack strongly affects summer low-flow magnitudes (Jenicek et al., 2016). Our more complete dataset of Swiss catchments indicates that winter precipitation (December through March) and SWE (on March 1st) are only weakly related to the magnitude and timing of the preceding warm-season low flows. In addition, these weak correlations did not significantly increase at higher elevation catchments, suggesting that even at the higher-altitude sites, SWE is not a major control on warm-season low flows. We caution the reader, however, that this analysis excludes many of the highest-altitude catchments, in which the annual low flow occurs during the winter (because we analyze only the lowest annual flows, not the lowest summer flows). Thus the discrepancy between our results and those of Jenicek et al., 2016 probably arises from differences between our respective definitions of low flows. We studied annual 7-day minima, and included only the annual low flows that occur between May and November (thus excluding many high-altitude sites where annual low flows occur in the winter instead), whereas Jenicek et al. (2016) studied 7-day summer minima regardless of whether they are annual minima. Thus, winter precipitation and SWE do affect summer streamflow in Alpine catchments (Jenicek et al., 2016), but our results suggest that for most of the rest of Switzerland, projected changes in winter snowpacks (e.g., Harpold et al., 2017; Mote et al., 2018) might only slightly affect the magnitude and timing of annual low flows that occur during the warm season.

4.3 Human impacts on low-flow statistics

Virtually every catchment in Switzerland, and elsewhere where dense gauging data exist, is to some extent affected by human activity (e.g., Grill et al., 2019, Lehner et al., 2011). This could be through, for example, water management operations, water abstractions, hydropower operations, and sewage treatment plant return flows. Especially in Central Europe, almost no pristine catchments exist and quantitative information capturing all potential human influences on streamflow at catchment scale is unavailable. As described in the methods, we removed any catchments with any obvious anthropogenic influences on streamflow (e.g., from hydropeaking or dams), however some regulation effects may still be present in the dataset.

To assess the impact of human influence across the Swiss catchments on the results, we recalculated Fig.1 c & d for the 20% of catchments with the largest fraction of human-affected landcover, and the 20% of catchments with the smallest fraction of human-affected landcover. As a proxy for human activity we use the Corine landcover dataset (CLC, 2018) and calculated the fraction of catchment area with “Artificial surfaces”. Thereby we tested whether the relationships between the 30-day anomalies of precipitation and PET and the magnitude of Q_{min} are significantly different in catchments with a lot of human activity compared to catchments with little human activity (Fig. 9). The results were broadly similar with no significant differences between the strongly affected and weakly affected catchments (p>0.2 by Student's t-test).

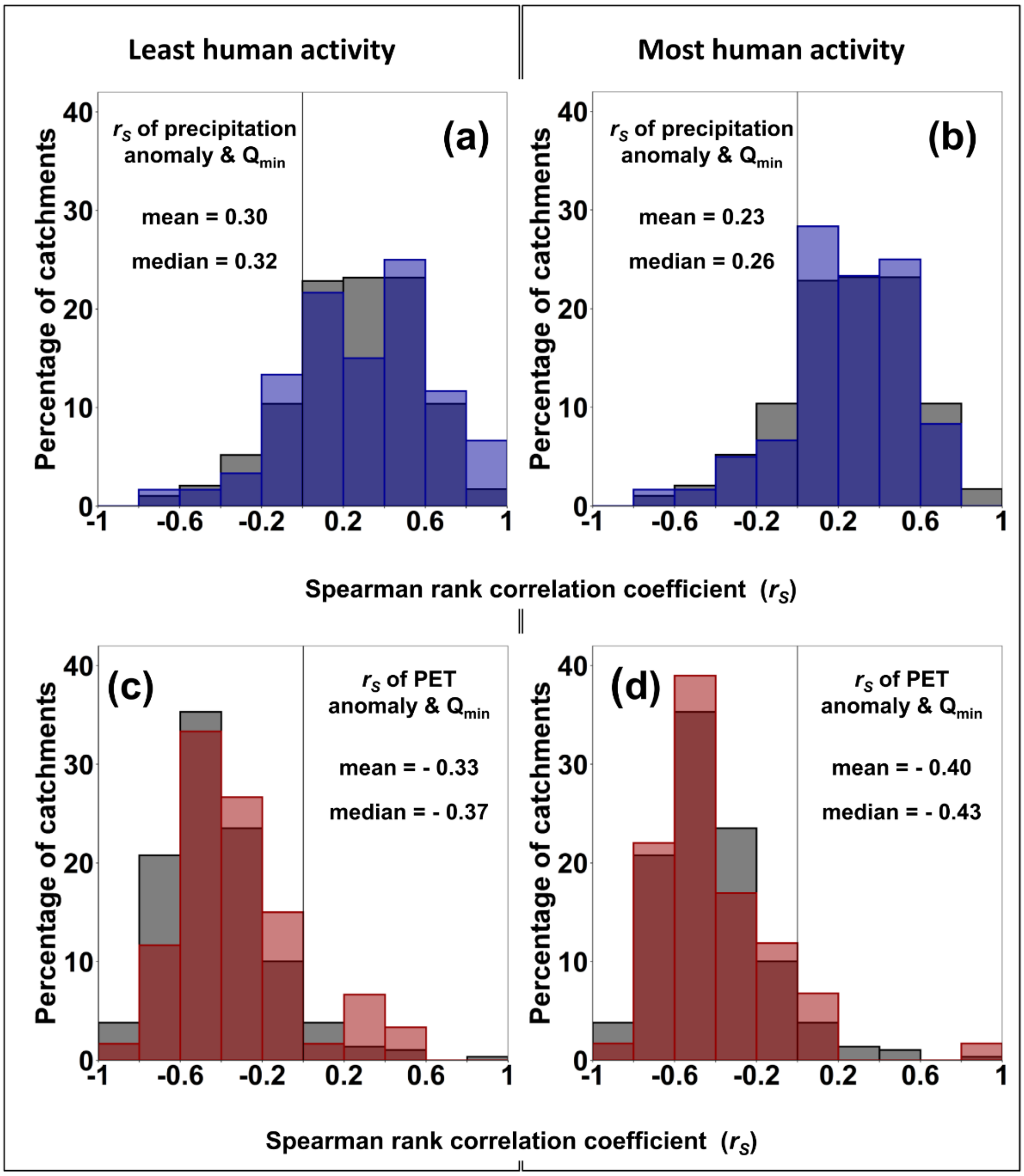

Figure 9: Histograms of rank correlations between anomalies of precipitation (a & b) and potential evapotranspiration (c & d) and low-flow magnitudes for late summer and autumn (May through November) low flows across Swiss catchments. On the left side (a & c) we show the distributions for the 20% of catchments with the least human impact (blue & red) on top of the distributions for all data (grey). On the right side (b & d) we show the distributions for the 20% of catchments with the most human impact (blue & red) on top of the distributions for all data (grey). The observed distributions of correlations between the 30-day climate anomalies and the magnitudes of low flows are similar in catchments with the most and the least human activity.

The consistency of the results may be due to the fact that, although human water usage during low flows will change their absolute magnitudes (and thus may affect site-to-site differences in low flows, which are not considered here), it may have a smaller effect on their relative magnitudes from year to year at any given site. Thus human influences may not greatly alter the rankings of annual low flows throughout the observation period; drier years are still expected to have lower low flows and wetter years are still expected to have higher low flows, largely independent of human influences. Therefore the Spearman rank correlation coefficient is likely to be a relatively robust index for assessing the effects of climate anomalies on the timing and magnitude of annual low flows. Recent studies across US catchments have also found limited effects of human influence on low flows compared to climate drivers (Ferrazzi et al., 2019; Sadri et al., 2016). Nevertheless, the unexplained variance in our established relationships suggests that human-induced shifts in the Q_{min} ranking may have an effect on low-flow behaviors in some catchments.

4.4 Broader implications

Our overall results are largely consistent with previously discussed drivers of low flows (e.g., Teuling et al., 2013; Woodhouse et al., 2016; Hannaford, 2015). Our work builds upon past research by studying a large dataset which shows the variability and consistency in low-flow/climate relationships among many catchments. We also quantify the effect of the duration of climate anomalies and analyze the interplay of P and PET as drivers. Our work thereby emphasizes how both precipitation and PET anomalies are important drivers of low flows, especially during severe low flows. This is in line with increased attention to severe events arising from the interplay of multiple drivers (e.g., Zscheischler et al., 2018). Our study also highlights that the relevant properties of low-flow drivers are multidimensional: their magnitudes, timings, and durations all matter. For example, in a lower-elevation catchment, a precipitation anomaly in spring will not have the same impact as a similar anomaly in autumn. Likewise, periods of above-average PET will have different implications for streamflow in May than they would in September. Thus, antecedent catchment conditions matter. It is not sufficient to look at climate anomalies alone as drivers of low flows, since they may have different implications at different times of the year. Although our study is based on a network of Swiss catchments, we expect our findings to be more broadly applicable to climatically similar regions as well. We see similar patterns in low-flow seasonality in other regions of the world (e.g., Laaha & Blöschl, 2006; Demirel et al., 2013; Dettinger & Diaz, 2000) suggesting that the effects of climate anomalies in these other regions may also be largely similar. For example, the severe summer low flows in California in recent years have been driven by below-average precipitation magnified by above-average temperatures and thus potential evapotranspiration (Diffenbaugh et al., 2015). Van Loon et al. (2015) and Van Loon & Laaha (2015) reported similar driving mechanisms for low flows in Austria and Norway. Thus, our approach for assessing the effects of multiple dimensions of climate impacts (i.e., timing, duration and magnitude) on low flows may be used to derive insight into low flows in other regions.

5. Conclusions

Annual low flows in Switzerland typically occur in two distinct seasons: in winter at higher elevations due to sub-freezing temperatures, and in summer and autumn at lower elevations, following periods of above-average potential evapotranspiration and below-average precipitation (Figs. 1a&b). The magnitudes of these climate anomalies strongly affect the magnitudes of annual low flows across our network of catchments (Figs. 1c&d). While both precipitation and PET anomalies can affect low flows, almost all (about 92%) of our catchments' annual low flows follow periods of unusually low precipitation, and many (about 70%) also follow periods of unusually high potential evapotranspiration (Fig. 2a). Thus, most low flows arise from the combined effects of precipitation and PET anomalies. Severe low flows, such as in the years 2003, 2011, 2015 and 2018, almost exclusively occurred after anomalies in both precipitation and PET (Fig. 2a). During these especially dry years, low flows occurred simultaneously across large parts of Europe, but their timing was highly variable across Switzerland (Fig. 3). Longer periods of below-threshold precipitation and above-threshold PET generally led to lower flows (Fig. 4). Anomalies preceding low flows typically acted over timescales of up to 60 days, while precipitation and PET anomalies in severe low-flow years (2003, 2011, 2015 and 2018) grew for much longer, and thus became much larger (Fig 5). Long periods of above-average PET appear to be especially important drivers of the most severe low flows (Fig. 5). Typical low flows were mainly driven by precipitation anomalies, however the low flows in the driest years (2003, 2011, 2015 and 2018) were strongly related to PET anomalies (Fig. 6 & 7). Total winter precipitation (and SWE) affected the magnitude and timing of summer and autumn low flows (Fig. 8), but was less important than the climate anomalies in the month prior to the low-flow period (Figs. 1c&d). However, the importance of snow processes for low flows occurring in winter remains to be analyzed. Our results describe how the timing, magnitude and duration of precipitation and PET anomalies drive low flows across Switzerland. In combination with seasonal weather forecasts, these results could help in predicting and managing low flows.

Data availability: The data that support the findings of this study are available in the ETH library open-access repository. Discharge time series can be obtained from FOEN (Swiss Federal Office of the Environment) and Swiss Cantonal Authorities; meteorological data can be obtained from MeteoSwiss, geodata from Swisstopo (Swiss Federal Office of Topography). Contact information for these agencies is provided in the Supplementary Material.

Author contribution: MF, WB, PM designed the study; MF performed the analyses and wrote the first draft, all authors discussed the results and edited the manuscript.

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