https://doi.org/10.5194/hess-2019-448
Preprint. Discussion started: 16 September 2019

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The effects of climatic anomalies on low flows in Switzerland

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Keywords: low flow, hydrological drought, precipitation, evapotranspiration

Short summary: Low river flows affect societies and ecosystems. Here we study how precipitation and potential evapotranspiration shape 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. Extreme low flows result from long periods of the combined effects of both drivers.

Abstract. Large parts of Europe have faced extreme low river flows in recent summers (2003, 2011, 2015, 2018) with major economic and environmental consequences. Understanding the origins of extremes like these is important for water resources management. To reveal how weather drives low flows, we explore how deviations from mean seasonal climatic conditions (i.e. "climatic 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 most extreme low flows resulted from both of these drivers acting together. Extremely dry years saw simultaneous drought conditions across large parts of Europe, but low-flow timing during these years was still spatially variable across Switzerland. Longer climatic anomalies led to lower low flows. Most low flows were typically preceded by climatic anomalies lasting up to two months, whereas low flows in the extreme years (2003, 2011, 2015, 2018) were associated with much longer-lasting climatic anomalies. Weather conditions on even longer time scales have been reported to sometimes affect river flow. However, across Switzerland, we found that precipitation totals in winter 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 summer and winter low flows across Switzerland, and could 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 droughts (Van Lanen et al., 2016). Their impacts, such as dry river reaches and high water temperatures, have had 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). Extreme droughts in the years 2003, 2011, 2015 and 2018 have 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 themselves become more frequent and intense (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).

Catchments' landscapes 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 direct drivers of low flows are meteorological conditions that dry out catchments (e.g., Fleig et al., 2006; Haslinger et al., 2014; Smakhtin, 2001). Low flows are not created instantaneously, but result from weather conditions acting over longer periods. Two main factors are precipitation and temperature (or potential evapotranspiration (PET)). We should expect unusually low flows to occur after weather conditions that are also exceptional, or at least that deviate from their typical patterns.

For example, precipitation controls the amount of water that is made available to a catchment, so a sustained lack of precipitation will inevitably reduce storage and thus limit streamflow. Because there is a time lag between precipitation and streamflow, meteorological droughts (i.e., precipitation deficits) result in a hydrological drought or a low flow if they persist for long enough (e.g., Peters et al., 2006; Tallaksen & Van Lanen, 2004; Van Loon, 2015). 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. Although these mechanisms are known, the effects of evapotranspiration on low-flow occurrences and magnitudes have received relatively little study. However, Seneviratne et al. (2012b) have reported that the extreme low flows of 2003 across Switzerland were most likely the result of evapotranspiration excess rather than spring precipitation deficits, and Teuling et al. (2013) have documented the depletion of water storage by high evapotranspiration during past European droughts. More recently Cooper et al. (2018) reported that low flows in the maritime Western US are largely driven by summer PET, rather than by winter precipitation or snow water equivalent. Furthermore, future PET is projected to increase along with increases in incoming longwave radiation (Roderick et al., 2014), with uncertain consequences for future low flows.

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. Godsey et al. (2014) found that decreasing snowpacks in the Sierra Nevada of California led to smaller low flows in the following summers. Similarly, Jenicek et al. (2016) reported that maximum snow accumulation strongly affected summer low flows across Switzerland. Dierauer et al. (2018) found that warmer winters with less snow accumulation led to smaller summer low flows in mountainous catchments of the Western United States. Future climate warming may thus reduce summer low flows, whether it comes in the summer (and thus increases PET), or in the winter, and thus reduces snowpack water storage (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 (e.g., Cooper et al., 2018; Dierauer et al., 2018; Seneviratne et al., 2012b; Shukla et al.,

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2015; Teuling et al., 2013; Van Lanen et al., 2016; Van Loon & Laaha, 2015; Woodhouse et al., 2016). Previous studies have largely focused on how statistics of low flows averaged across many years are connected to climate characteristics (e.g., Laaha & Blöschl, 2006; Floriancic et al., in review). However, because low flows are exceptional flow conditions, they should be expected to follow atypical weather conditions, rather than climate seasonality. Therefore, we hypothesize that low flows will typically occur after anomalous weather conditions, that is, weather conditions that deviate substantially from the seasonal norm. We also hypothesize that the most extreme low flows will be associated with the most extreme weather anomalies. Understanding how anomalous weather drives low flows may help to reveal the processes at work, and also may support low-flow forecasting.

Here we explore how precipitation and PET deviations from seasonal norms (here termed "climatic anomalies") together shape the occurrence and magnitude of annual low flows across a network of 380 Swiss catchments. Switzerland is a useful study region because gauging and climate data are available from a dense station network, for catchments spanning a wide range of elevations, climates, and topographies. We investigate (a) how precipitation and PET anomalies together shape the occurrence and magnitude of low flows across Switzerland, (b) how the durations of these anomalies influence low-flow occurrence and magnitude, both in typical and in exceptionally dry years, and (c) how winter precipitation influences 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 become more typical in a future warmer climate.

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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. We defined low flows 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). The catchments range in size from 1 to 519 km^2, range in mean elevation from 309 to 2930 m, and are distributed across different regions with diverse landcovers and climates. We used daily gridded precipitation and temperature data (~2x2 km cells; Meteoswiss products RhiresD and TabsD) to derive catchment-averaged weather and climatic conditions. We quantified daily potential evapotranspiration (*PET*) following the method of Hargreaves & Samani (1985).

2.2. Anomalies of climatic variables

To infer which climatic 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 whose lowest annual flows were much higher than typical low flows. We removed unusually high annual low flows that exceeded three standard deviations above the catchment mean of all annual low flows; this 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 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 climatic 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:

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

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 of September 2018 minus the mean of precipitation for all Septembers from 2000 to 2018. We calculate *PET* anomalies in an equivalent manner. We quantify the correlations between these anomalies and annual low-flow characteristics using Spearman rank correlation coefficients (r_S) and test for consistent differences in our results with the sign test.

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3. Results and Discussion

3.1 Seasonality of low flows

Low flows in Switzerland mostly occur during two distinct seasons, depending primarily on mean basin elevation (Fig. 1). Low flows in lower-elevation catchments (i.e., below 1200 m asl) tend to occur in late summer and early autumn (August, September, October), whereas in higher-elevation catchments (above 1200 m asl) most low flows occur during winter (February and March). The existence of two distinct low-flow seasons is not unique to Switzerland, but has also been reported for many other regions of the world, including, for example, Austria, the Rhine river basin, and the United States (e.g., Cooper et al., 2018; Dierauer et al., 2018; Laaha & Blöschl, 2006; Van Loon & Laaha, 2015; Demirel et al., 2013; Tongal et al., 2013; Wehren et al., 2010; Floriancic et al., in review). The existence of two distinct low-flow seasons (Fig. 1) hints at the weather conditions driving these low flows: warm-season low flows are typically caused by sustained periods of high evapotranspiration and low precipitation, whereas winter low flows are often caused by sustained periods of sub-freezing temperatures (e.g., Laaha et al., 2013; Van Loon, 2015; Floriancic et al., in review). It is therefore likely that precipitation and PET anomalies are important drivers of summer low flows, but not winter low flows. However, this remains to be tested.

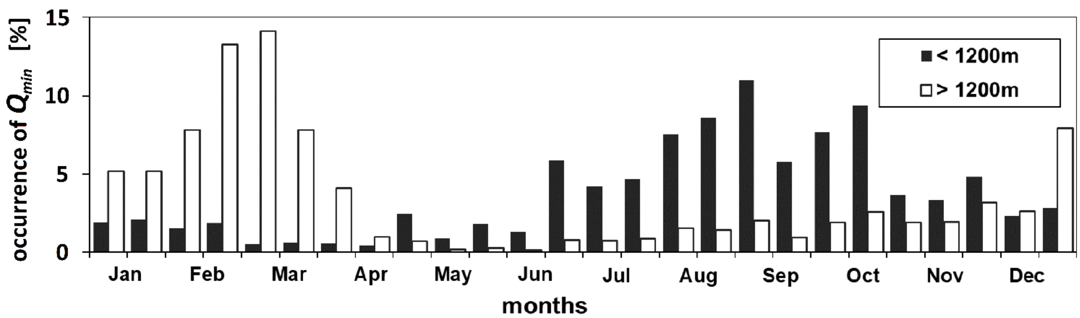

Figure 1: Seasonal distribution of low flows, represented by the fraction of the 380 catchments in which Q_{min} occurred during a given month, grouped by elevation. Low flows in catchments above a mean elevation of 1200 m typically occur during the winter months (white bars), whereas low flows in catchments with mean elevations below 1200 m typically occur in late summer and early autumn (black bars).

3.2 Climatic anomalies control low-flow timing and magnitude

Beyond the broad seasonal patterns illustrated by Fig. 1, the low-flow timing is clearly linked to periods of below-average precipitation and above-average *PET* (Fig. 2a&b). However, again distinct regional differences exist: at low elevations, almost all annual low flows occur after periods of anomalously high potential evapotranspiration and anomalously low precipitation (Fig. 1a&b). At elevations above 1200 m (the horizontal line - in Fig. 2a&b), 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, 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 and 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 often be the length of the freezing period, rather than how far below zero these temperatures were, or how much precipitation occurred.

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The patterns that we observe here are probably not unique to Switzerland; we expect precipitation and *PET* anomalies to be relatively unimportant in other mountain regions where low flows primarily occur in winter (e.g., Dierauer et al., 2018; Van Loon et al., 2015; Laaha & Blöschl, 2006), driven by extended subfreezing periods. However, summer low flows are more common globally (e.g., Dettinger & Diaz, 2000; Eisner et al., 2017), suggesting that climate anomalies are important not only for lower-elevation catchments in Switzerland, but across many other regions of the world. From here on, we focus on the drivers of warm-season low flows, occurring from July through November at our study catchments.

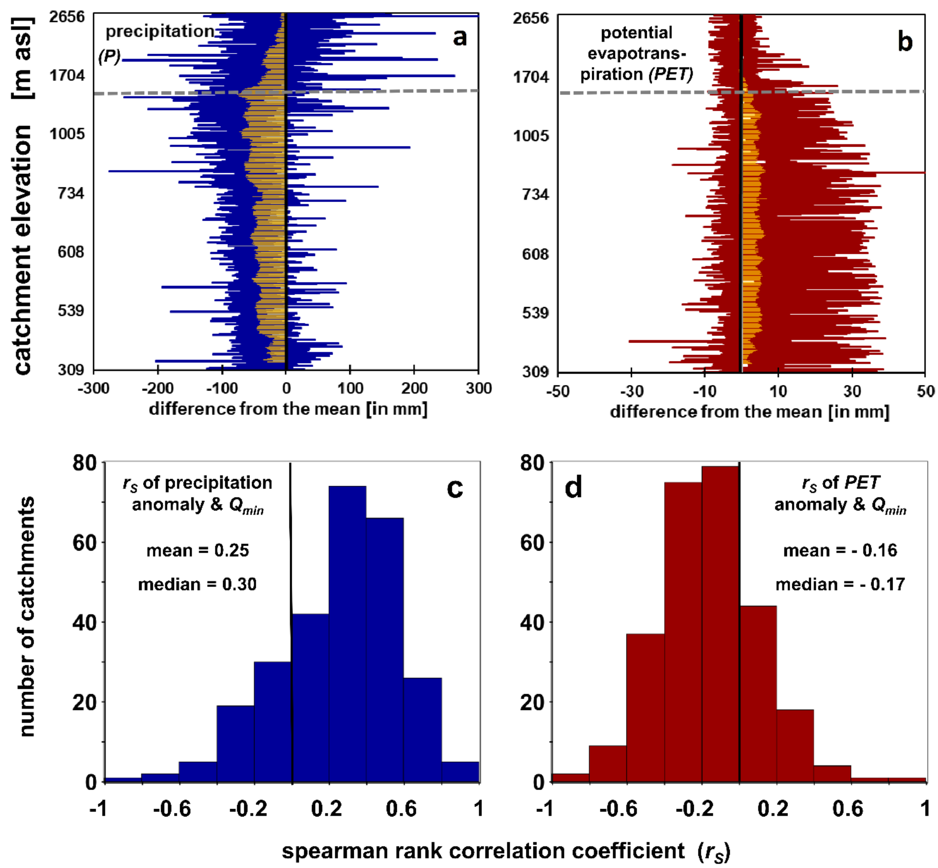

Figure 2: Altitudinal variation in 30-day anomalies of precipitation (a) and potential evapotranspiration (b) preceding annual low flows. Blue and red horizontal bars indicate the range between the minima and maxima of these anomalies at each catchment across the 19 years of this study. Yellow bars show moving averages of these climatic 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), except above elevations of roughly 1200 m (dashed grey line), where *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 (July 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.

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More extreme climatic anomalies tend to lead to lower low flows (Fig. 2c&d). Spearman rank correlations of magnitudes of the climatic anomalies to magnitudes of Q_{min} (shown for the months June through November) indicate that lower precipitation in the 30 days prior to Q_{min} usually results in smaller Q_{min} (median r_S=0.3). Similarly, higher potential evapotranspiration usually results in smaller Q_{min} (median r_S=-0.17). 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.

3.3 Combined effects of climatic anomalies on (extreme) low flows

Our previous results (Fig. 2) 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 July through November, usually follow periods of below-average precipitation and above-average potential evapotranspiration (70% of low flows fall in the top left quadrant of Fig. 3a). Fewer than a quarter of the annual low flows occur after periods of below-average precipitation and below-average potential evapotranspiration (22% lower left quadrant – Fig. 3a). Only very few annual low flows (8%) 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, 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 extreme low flows occur through the combined effects of low precipitation and high potential evapotranspiration. For example, 94% of low flows during the most extreme low-flow year (2003, shown by green markers in Fig. 3a) 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 extreme annual low flows such as 2011, 2015 and 2018 (Fig. 3b&c). This is consistent with earlier studies that highlight both precipitation and evapotranspiration as combined drivers of extreme low flows in several experimental catchments during the 2003 drought (Seneviratne et al., 2012b; Teuling et al., 2013). The pronounced effect of *PET* might also reflect higher air temperatures and lower relative humidity due to depleted soil moisture, which will increase *PET* even more. As summer low flows are not unique to Switzerland, we expect that the compound effects of *PET* and precipitation anomalies are also important for low flows in many other regions.

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. 3a). These anomalies are expected to lead to above-average flow conditions, but still can lead to annual low flows for a number of 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 (Floriancic et al., in review; 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.

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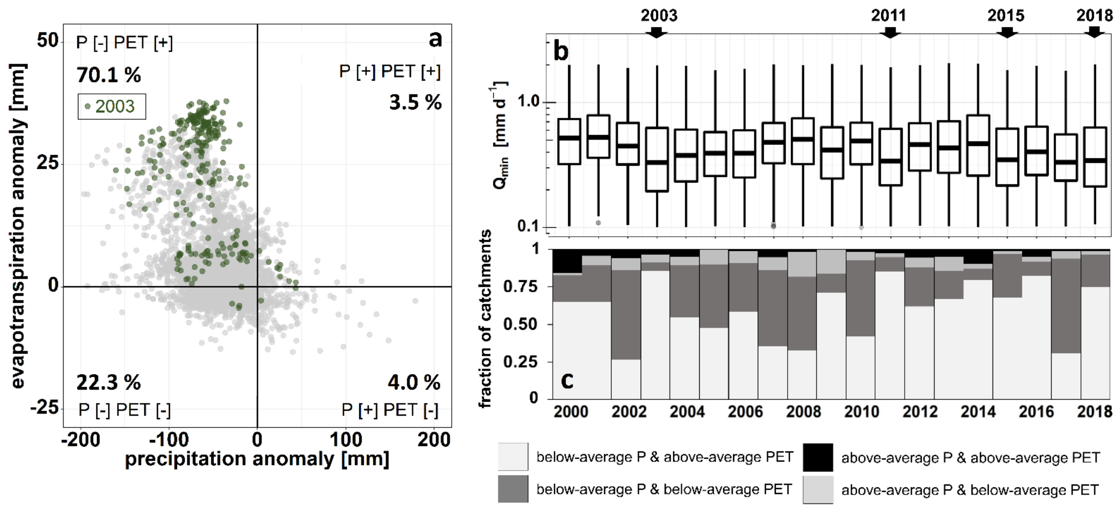

Figure 3: Anomalies in precipitation and potential evapotranspiration 30 days prior to each annual late summer and autumn (July through November) low-flow period in each catchment (grey dots); winter low flows were excluded (a). The most extreme low-flow year during the study (2003) is highlighted in green. Almost all (92.4%) annual low flows occurred following below-average precipitation (the left half of the figure), and 70.1% of all low flows occurred following a combination of below-average precipitation and above-average potential evapotranspiration (the upper left quadrant of the figure). By contrast, only 4% of points plot in the lower right quadrant, corresponding to above-average precipitation and below-average potential evapotranspiration. The extreme low flows of 2003 were associated with below-average precipitation, and with a particularly severe anomaly in potential evapotranspiration. Boxplots of annual 7-day minimum flows 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 extremely dry years of 2003, 2011, 2015, and 2018, drought conditions occurred simultaneously across large parts of Europe (Laaha et al., 2017; Van Lanen et al., 2016). However, across Switzerland annual low flows did not occur simultaneously, but instead occurred primarily during the winter in the Alpine regions and the summer and autumn in the Swiss Plateau (Fig. 4). In addition, within these two sub-regions, the timing of low flows was still spatially variable, indicating that synchronous drought across Europe does not necessarily imply synchronous annual low flows across Switzerland. Within the Swiss Plateau, low-flow timing is more spatially consistent during some (non-extreme-drought) years (e.g. 2009, 2013, 2016), than during others (e.g. 2000, 2002, 2004, 2010, 2017).

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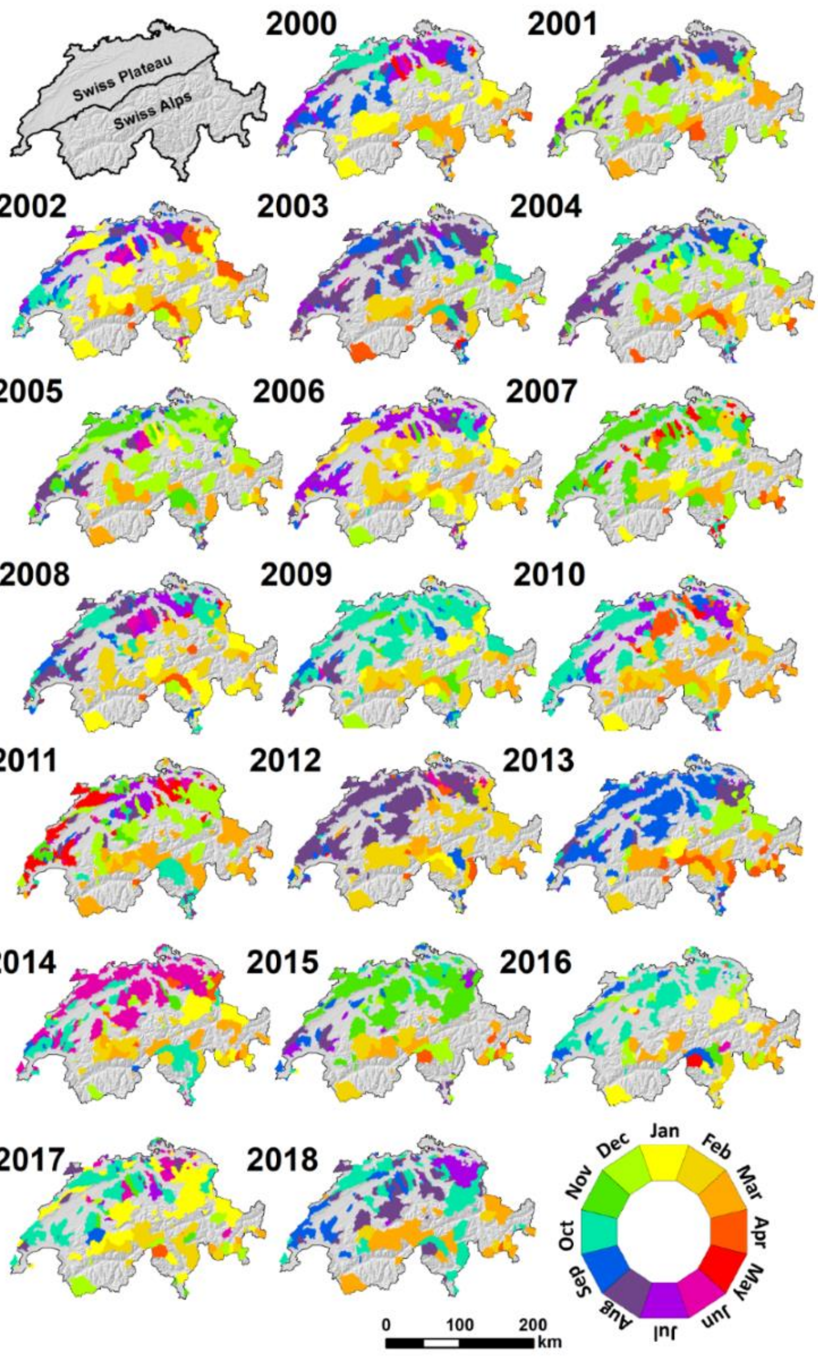

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Figure 4: The timing of occurrence of annual low flows across Switzerland for the years 2000 to 2018 in the two main regions: the Swiss Plateau and Swiss Alps (roughly the northern and southern halves of the country, respectively). Low-flow timing tends to be spatially heterogeneous, even in years when large parts of Europe simultaneously experienced severe droughts (2003, 2011, 2015, 2018).

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3.4 Duration of climatic 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. 5). 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 -0.09 respectively; p-values < 0.001; Fig. 5). The weaker correlation with the duration of below-threshold precipitation probably arises because precipitation is more erratic than *PET*. A single brief precipitation event may exceed the precipitation threshold (according to the criteria outlined in the caption to Fig. 5), but not nearly enough to end the low flow in the stream. The duration of below-threshold precipitation is less strongly correlated with low-flow magnitudes than the intensity of 30-day precipitation anomalies is (compare Fig. 5 with Fig. 2; mean r_S of -0.09 and 0.25, respectively). Conversely, the duration of above-threshold *PET* is more strongly correlated with low-flow magnitudes than the intensity of 30-day *PET* anomalies is (compare Fig. 5 with Fig. 2; mean r_S of -0.16 and -0.27, respectively).

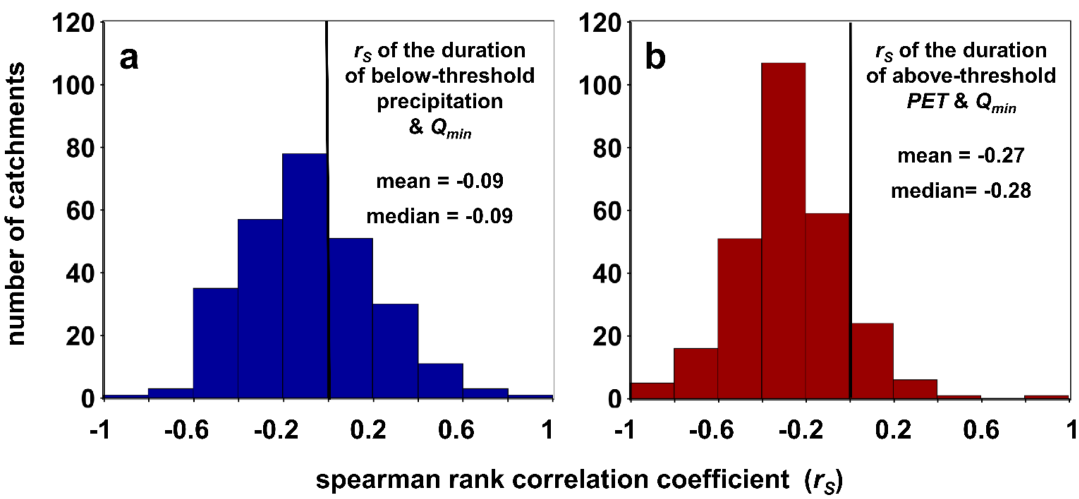

Figure 5: Histograms of rank correlations between the magnitudes of late summer and autumn (July through November) low flows and the lengths of the preceding intervals with low precipitation (a) or high *PET* (b). The threshold that defines low precipitation is the 20th percentile of the 10-day running averages of precipitation over the entire period of record. Similarly, the threshold that defines high *PET* is the 80th 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. 6). This is because in the typical Swiss climate, precipitation and *PET* anomalies usually last for 60 days or less. This is depicted by the gray cloud of points in Fig. 6, as well as the mean anomalies (indicated by the dotted lines in Figs. 6a-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 because most anomalies peak at around that time scale; this is also indicated by the mean of precipitation and *PET* anomalies as a function of timescale (dashed line in Figs. 6h and 6i).

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Extreme low flows (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. 6). Long periods of above-average *PET* appear to be an important factor for these extreme low flows; the colored points in Figs. 6e-g expand more on the y-axis than the x-axis for timescales >60 days. Thus, extreme low flows result from longer-lasting (and thus larger) precipitation and *PET* anomalies, whereas more typical low flows result from climatic anomalies that end after roughly 60 days, as illustrated by Figs. 6h&i. Seneviratne et al., 2012b and Teuling et al., 2013 have documented the effects of long-duration *PET* anomalies on low flows in several small experimental catchments; here we show that these anomalies are also important controls on extreme low flows in a large, diverse sample of mesoscale catchments.

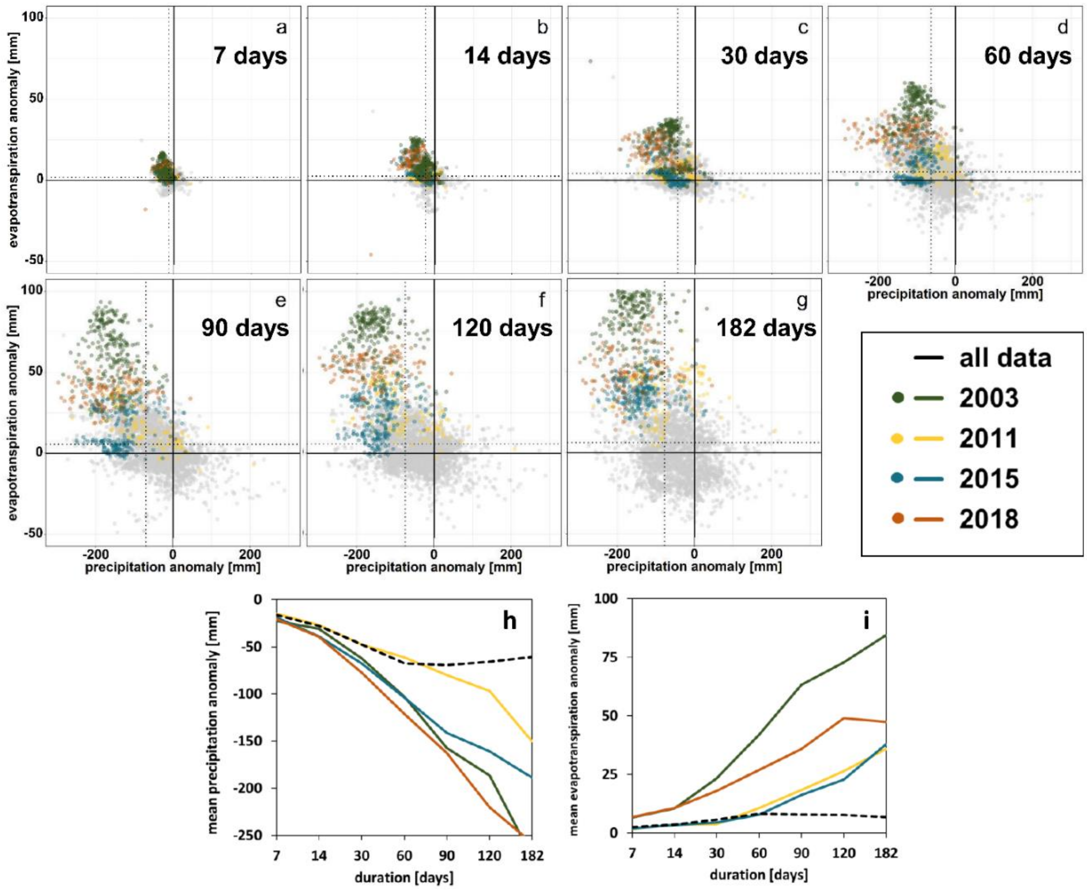

Figure 6: Cumulative anomalies of precipitation and potential evapotranspiration over 7, 14, 30, 60, 90, 120 and 182 days prior to every annual late summer and autumn (July through November) low flow in each catchment (a-g), and the evolution of the mean anomalies over the different time windows (h & 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, whereas the precipitation anomalies do not extend as far beyond the range that is typically observed.

3.5 The influence of winter precipitation on low flows

Previous studies have indicated 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 (December through March) precipitation should lead to larger and later summer/autumn low flows. To test this, we calculated Spearman rank correlations between winter precipitation totals and subsequent low-flow magnitudes and timing. These correlations (mean $r_S < 0.15$ for both; p-values < 0.001; Fig. 7) are somewhat weaker than those between low flow magnitudes and climatic anomalies in the period directly before the low flow (Figs. 2c&d), and they do not vary with altitude.

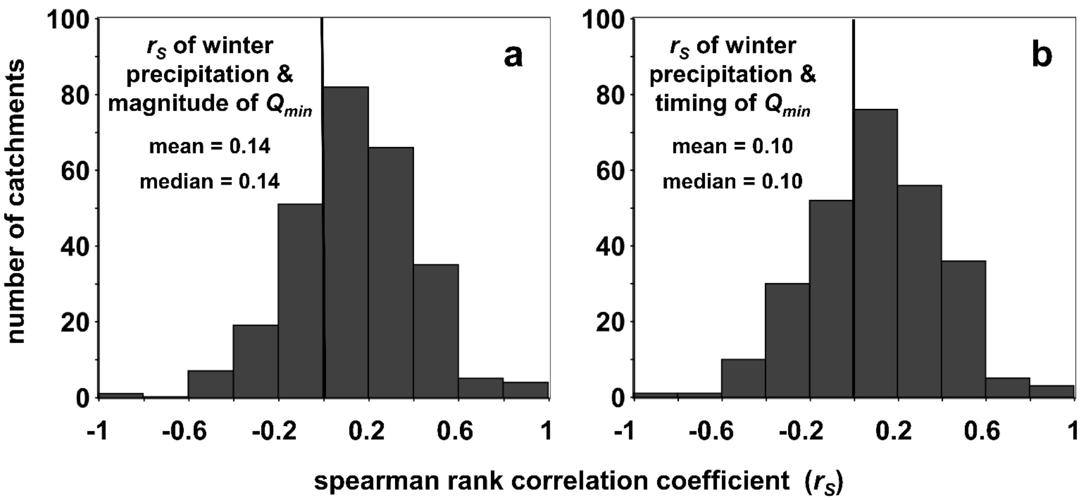

Figure 7: Histograms of the rank correlations between winter precipitation (December through March) and the magnitude (a) and timing (b) of summer low flows (July through November). Winter precipitation is weakly associated with higher, and later, low flows, as indicated by the positive r_S for the majority of catchments.

Previous work in several Swiss catchments has suggested that the snow-water equivalent (SWE) accumulated in the winter snowpack is an important factor determining summer low-flow magnitudes (Jenicek et al., 2016). Our analyses reveal only weak correlations between the magnitude of winter precipitation and summer low-flow magnitudes. These weak correlations may be partly because winter precipitation sums do not always accurately represent SWE (Rasmussen et al., 2012). However, if SWE is important, we expect to see stronger correlations between winter precipitation and summer low flows at higher elevations, where winter precipitation will more closely correspond to annual peak SWE. However, we do not see these stronger correlations, suggesting that even at the higher-altitude sites, SWE is not a major control on summer/autumn 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 in the definition of low flows. We study annual 7-day minima, and include only the annual low flows that occur between July and November (thus excluding many high-altitude sites where annual low flows occur in the winter instead), whereas Jenicek et al. (2016) study 7-day summer minima regardless of whether they are annual minima. Thus, winter precipitation does effect summer streamflow in Alpine catchments (Jenicek et al., 2016), but our results suggest that for most of Switzerland, projected changes in winter snowpacks (e.g. Harpold et al., 2017; Mote et al., 2018) will only slightly affect annual low flows that occur during summer.

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3.6 Broader implications

To date most work has discussed individual drivers of low flows (e.g., Fangmann & Haberlandt, 2019; Hannaford, 2015; Marengo & Espinoza, 2016) rather than analyzing the interplay of drivers. Our work emphasizes how both precipitation and *PET* anomalies are important drivers of low flows, especially during extreme droughts. This is in line with increased attention on extreme events arising from the interplay of multiple coupled 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. Although our study is based on a network of Swiss catchments, we expect our findings to be more broadly applicable to other 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 is these other regions may also be largely similar. For example, the severe Californian summer droughts 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 framework for assessing the multiple dimensions of climatic impacts on low flows may be applicable to other regions worldwide; this can and should be tested in further studies.

https://doi.org/10.5194/hess-2019-448
Preprint. Discussion started: 16 September 2019

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4. Conclusions and summary

Typical annual low flows (Q_{min}) in Switzerland occur in two distinct seasons (Fig. 1). Above 1200 m, low flows tend to occur in winter due to sub-freezing temperatures; below 1200 m they tend to occur in summer and autumn, after periods of above-average potential evapotranspiration and below-average precipitation (Figs. 2a&b). The magnitudes of these climatic anomalies strongly affect the magnitudes of annual low flows across our network of catchments (Figs. 2c&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. 3a). Thus, most low flows arise from the compound effects of precipitation and *PET* anomalies. Extreme low flows, such as in the years 2003, 2011, 2015 and 2018, almost exclusively occurred after anomalies in both precipitation and *PET* (Fig. 3). During these extremely dry years, low flows occurred simultaneously across large parts of Europe, but their timing was highly variable across Switzerland (Fig. 4). Longer periods of below-threshold precipitation and above-threshold *PET* generally lead to lower flows (Fig. 5). Anomalies preceding typical low flows act over timescales of up to 60 days, while precipitation and *PET* anomalies in extreme low-flow years (2003, 2011, 2015 and 2018) grow for much longer, and thus become much larger (Fig 6). Long periods of above-average *PET* appear to be especially important as drivers of extreme low flows (Fig. 6). Total winter precipitation (mostly consisting of snowfall) affected the magnitude and timing of summer and autumn low flows (Fig. 6), but was less important than the climatic anomalies in the month prior to the low-flow period (Figs. 2c&d). 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 from the corresponding author upon request.

Author contribution: MF, WB, PM designed the study; MF performed the analyses, all authors edited the manuscript.

Competing interests: The authors declare that they have no competing interests.

Acknowledgements: The project was funded by the Swiss Federal Office of the Environment (FOEN). We thank FOEN and the Cantons Aargau, Basel Landschaft, Bern, Geneva, Graubünden, Luzern, Neuchatel, Schaffhausen, Solothurn, St.Gallen, Thurgau, Ticino, Vaud and Zürich for providing discharge data, the Swiss Federal Office of Meteorology (Meteoswiss) for providing gridded climate data and the Swiss Federal Office of Topography (Swisstopo)for providing geodata.

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