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Seasonality and Drivers of Low Flows Across Europe and the United States

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Key Points:

- Across Europe and the US, seasonal patterns in low flows and potential low-flow drivers (precipitation, ET, and freezing) vary regionally
- For 1860 catchments in Europe and the US we assign (and exclude) dominant drivers of annual low flows using binomial statistics
- Most low flows occur in late summer driven by ET, but in cold regions low flows often occur in winter driven by freezing

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Low river flows can negatively impact society and the riverine environment. Thus, it is useful to predict their seasonal timing and reveal their main drivers. The typical timing of low flows varies between regions, yet systematic overviews across Europe and the United States are rare. Here, we identify regional patterns of the seasonal timing of annual minimum flows, and the consistency of that timing, across 1860 European and US catchments. Catchments where low flows typically occur during late summer or winter tend to have more consistent low-flow timings. We compare the timing of annual low flows with that of potential climatic drivers. Low flows in 89% of the European and 86% of the US catchments exhibit a statistically significant ($p < 0.05$) overlap in timing with at least one potential climatic driver. In most catchments, low flows tend to occur during the warm season, reflecting a period of high potential evapotranspiration exceeding precipitation. In the higher elevation European Alps, Scandinavia, the Rocky Mountains, and the Upper Midwest and Plains states, low flows mostly occur during winter as a result of freezing temperatures which inhibit snowmelt. Binomial statistics also enabled us to statistically exclude individual climatic drivers for certain regions. The regional patterns of timings and drivers of low flows across Europe and the contiguous US can inform low-flow management, provide context for the evolution of low flows under climate change, and point to processes that require attention in future low-flow research.

1. Introduction

Low river flows affect water quality and river ecology, as well as water availability for industry, agriculture, and navigation (e.g., Bradford & Heinonen, 2008; Laaha et al., 2013; Poff et al., 1997; van Vliet et al., 2012). The timing of low flows, and potential future shifts in that timing, affect instream habitats and biotic interactions and limit water availability for household use, irrigation, artificial snow production, and hydropower (e.g., Lake, 2003, 2011; Ledger & Milner, 2015; Poff et al., 1997; Stahl et al., 2016). Low flows in headwaters can propagate downstream through the river network, creating negative impacts far from the source areas. The effects of low flows may grow under climate change (e.g., Feyen & Dankers, 2009; Marx et al., 2018), with longer dry spells, more heatwaves, and reduced snowpacks (e.g., Berghuijs et al., 2014; Eisner et al., 2017; Milly et al., 2005). Thus, predicting low-flow characteristics is of both economic and environmental interest.

The magnitudes and seasonal timings of low flows vary between geographic regions, reflecting many different climatic, landscape, and anthropogenic factors, including precipitation, temperature, potential evapotranspiration, bedrock geology, soil properties, topography, and land use (e.g., Blöschl et al., 2013; Douglas et al., 2000; Giuntoli et al., 2013; Kennard et al., 2010; Kormos et al., 2016; Laaha & Blöschl, 2006a; Lins & Slack, 1999; Pearson, 1995). Low-flow timing has previously been analyzed for several catchments and regions (e.g., Burn et al., 2008; Garbrecht et al., 2004). For example, low-flow seasonality has been studied across Switzerland (Wehren et al., 2010), the United Kingdom (Young et al., 2000), Austria (Laaha & Blöschl, 2006b), the United States (Pournasiri Poshtiri et al., 2019), and parts of eastern Germany (Fangmann & Haberlandt, 2019). Low-flow seasonality has been used for regionalization purposes and to assess climate change impacts (e.g., Laaha & Blöschl, 2006b; Demirel et al., 2013; Vezza et al., 2010). Although seasonal patterns in streamflow and flooding have been characterized at continental and global scales (e.g., Berghuijs et al., 2019; Dettinger & Diaz, 2000; Do et al., 2019; Eisner et al., 2017), similar large-scale systematic overviews of low-flow timing are rare.

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Table 1
Attributes of Global Runoff Data Centre (GRDC) and CAMELS Catchments Selected for Use in This Study

		Europe	United States
		GRDC	CAMELS
Number of Catchments	<i>n</i>	1190	670
Catchment Size (km ²)	Median (min–max)	276 (0.6–10,667)	329 (4–25,791)
Elevation (m a.s.l.)	Median (min–max)	153 (1.7–1995)	463 (17–3,185)
Mean Air Temperature (°C)	Median (min–max)	7.7 (–8.2–14.1)	11.0 (–0.7–22.8)
Time Period Covered	Years	1980–2014	1980–2014

The seasonality of low flows can help in inferring the climatic conditions driving them (e.g., Dettinger & Diaz, 2000; Van Loon & Van Lanen, 2012). Typical climatic drivers of low flows include low precipitation, high evapotranspiration, freezing, or combinations thereof (e.g., Blöschl et al., 2013; Dierauer et al., 2018; Floriancic et al., 2020; Teuling et al., 2013; Van Loon et al., 2015). Connections between climatic drivers and flood seasonality have been studied at the continental scale (e.g., Berghuijs et al., 2016; Blöschl et al., 2017), but assessments of the timing and drivers of low flows are only available for a limited number of catchments or regions (e.g., Cooper et al., 2018; Dierauer et al., 2018; Floriancic et al., 2020; Laaha & Blöschl, 2006a; Van Loon et al., 2015; Van Loon & Van Lanen, 2012). Systematic large-scale assessments of low-flow seasonality and drivers can inform water management by revealing when low flows are likely to occur and by providing context for anticipating regionally varying climate change impacts on low flows.

Here, we use streamflow data from 1860 gauging stations to provide a data-driven assessment of low-flow seasonality across Europe and the contiguous United States (US). By comparing the annual timing of low flows and their potential drivers (precipitation, excess potential evapotranspiration, and low temperature), we infer the potential drivers of low flows across continental scales. Together, these analyses illuminate when low flows typically occur, and which climatic drivers most likely control their occurrence.

2. Data and Methods

2.1. Streamflow and Climate Data

Our analysis is based on river gauging and climate data sets covering Europe and the contiguous United States (Table 1). For Europe, we use Global Runoff Data Centre (GRDC) mean daily streamflow values from 1190 catchments. We only analyze streamflow time series that extend at least until the end of 2012 and have 90% complete daily records between 1980 and 2014. This time period was chosen to be relatively recent and to provide temporal overlap between the regions. The catchments range from 0.6 to 10,667 km² (median = 276 km²) in size, from 2 to 1995 m a.s.l. (median = 153 m a.s.l.) in mean elevation, and from –3 to 16°C (median = 8°C) in mean air temperature. Unfortunately, no sufficiently recent GRDC streamflow time series are available for most southern European countries, including Spain, Italy, Portugal, and the Balkans, resulting in their exclusion from our analysis. We obtained daily gridded precipitation and minimum, maximum, and mean temperature from the E-OBS (version 20.0e) data set at 0.1-degree resolution covering the period 1980–2014 (Cornes et al., 2018). We calculated daily *PET* according to the Hargreaves equation, averaged over each catchment area for the period 1980–2014. For most catchments, boundaries can be downloaded from the GRDC; the few missing ones were obtained from the GSIM data set (Do et al., 2018).

For the contiguous United States, we use 670 catchments of the CAMELS data set (Addor et al., 2017), spanning a wide range of different climates and landscapes. The catchments range in size from 4 to 25,791 km² (median = 329 km²), with mean elevations ranging from 17 to 3,185 m a.s.l. (median = 463 m a.s.l.) and mean annual air temperatures ranging from –1 to 23°C (median = 11.5°C). The discharge data cover the period 1980–2014 at daily resolution. The climate data (daily precipitation, daily mean temperature, daily *PET*) and the catchment boundaries are all included in the CAMELS data set.

2.2. Seasonality of Low Flows and Climatic Drivers

We quantify the timing of low flows and their climatic drivers using the same directional statistics (Bayliss & Jones, 1993; Burn, 1997) that have been widely used to characterize the seasonality and climatic drivers of floods (e.g., Berghuijs et al., 2016; Blöschl et al., 2017; Köplin et al., 2014), and have also been applied in previous low-flow analyses (e.g., Tian et al., 2011; Wehren et al., 2010; Young et al., 2000). We define the annual low flows by the lowest 7-day average streamflow each year (Q_{min}), which is a commonly used indicator of low flows (e.g., Jenicek et al., 2016; Kam & Sheffield, 2016; Laaha et al., 2017; Riggs, 1980; Van Lanen et al., 2016; Vogel & Kroll, 1992). The Q_{min} dates analyzed here are the centers of these 7-day lowest streamflow periods in each year and each catchment. The mean dates of occurrence D (day of the year) of Q_{min} and of the climatic drivers are calculated by:

$$D = \begin{cases} \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) \cdot \frac{\bar{m}}{2\pi} & \bar{x} > 0, \bar{y} \geq 0 \\ \left(\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + \pi\right) \cdot \frac{\bar{m}}{2\pi} & \bar{x} \leq 0 \\ \left(\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + 2\pi\right) \cdot \frac{\bar{m}}{2\pi} & \bar{x} > 0, \bar{y} < 0 \end{cases} \quad (1)$$

where

$$\bar{x} = \frac{1}{n} \sum_{k=1}^n \cos(\theta_k) \quad \bar{y} = \frac{1}{n} \sum_{k=1}^n \sin(\theta_k) \quad (2)$$

and where \bar{m} is the average length of a year (in days), n is the number of studied years at each site, \bar{x} and \bar{y} are calculated from the cosines and sines of the dates of occurrence for each year k expressed in radians (θ_k). The mean cosines and sines \bar{x} and \bar{y} are also used to calculate the consistency of the timing

$$F = \sqrt{\bar{x}^2 + \bar{y}^2} \quad (3)$$

where $F \rightarrow 1$ indicates that annual low flows consistently occur at nearly the same time every year, whereas $F \rightarrow 0$ indicates that annual low flows occur at widely differing times of the year.

2.3. Inferring Climatic Drivers of Low Flows

Low flows can be caused by several different climatic drivers. Low-flow timing can help in inferring these drivers by comparing the seasonality of the low flows with the seasonality of potential climatic drivers. Because catchments integrate the effects of their climatic drivers over time, the timing of annual low flows should reflect the date that the cumulative impact of the climatic driver reaches its peak. For example, high evapotranspiration rates during summer result in low flows at the end of summer (when the cumulative impact of evapotranspiration is greatest) rather than in midsummer (when the instantaneous rate of evapotranspiration is greatest).

Precipitation deficits may cause low flows (Smakhtin, 2001; Van Loon, 2015). Summer and autumn low flows often result from periods where evapotranspiration exceeds precipitation, whereas winter low flows often result from extended freezing periods without liquid precipitation or snowmelt (e.g., Garbrecht et al., 2004; Laaha et al., 2013). Therefore, we formulate the following three potential climatic drivers of low flows: periods of (a) low precipitation, (b) high excess potential evapotranspiration, and (c) low air temperatures. These are not intended as detailed mechanistic descriptions of how low flows are generated. Instead, they represent distinct climatic drivers for the purpose of inferring which of them is dominant in causing low flows, and which one is not.

We assume that these climatic drivers need to be low (or high) over a time window in order to cause an annual low flow. We therefore sum each driver over running 30-day windows and find the annual extremes of these 30-day running sums (the sensitivity analysis presented in Figure S1 shows that another choice of window length, e.g., 60 days, yields consistent results). The date of occurrence of a climatic driver is defined by the last day of the 30-day window because each driver is expected to act to reduce streamflow over the whole period that it is active. We then calculate the mean date of occurrence (D) of the annual minima (or maxima) and the consistency of those dates (F) for all climatic drivers.

We quantify the similarity in timing between low flows and the three potential drivers using binomial statistics. We first tally the number of years in which the annual low flow of a particular year coincides with the annual climatic extreme for each candidate driver of that same year within plus or minus 30 days. Under the null hypothesis that annual low flows are randomly associated with each of these annual climatic extremes, we would expect such coincident timing to occur randomly 16.4% (61/365) of the time. The duration of 61 days is chosen to allow for a hydrologically meaningful delay between the causes and effects of low flows. Using the binomial distribution for the total number of years at each site, we calculate the statistical significance (p -value) of the number of years in which the annual low flow coincides with the candidate driver. This p -value expresses how improbable the observed number of timing coincidence would be, in the absence of any association between climatic extremes and low flows. At most of our sites, with 34 years of record, p -values of 0.05, 0.01, 0.001, and 0.000015 correspond to 10, 12, 14, and 17 years with coincident timing.

We can also use a similar approach to statistically rule out candidate drivers for individual sites. Again assuming the null hypothesis of random association between low flows and climatic extremes, we would expect them to not coincide (by more than plus or minus 30 days) with a frequency of 83.6% (305/365). We can thus use the binomial distribution for each site to determine whether these “misaligned” years (in which low flows do not coincide with climatic extremes) arise more frequently than expected by chance. However, because the rate of misalignment under the null hypothesis is so high, the power of this test is relatively low. Nonetheless, for example, out of 34 years of record, 33 and 34 misaligned years correspond to p -values of 0.02 and 0.002, respectively. Thus, when low flows and climatic drivers are misaligned in their timing this often, we can infer that they coincide significantly less frequently than expected by chance.

2.3.1. Low Precipitation

When precipitation is low over an extended period, streamflow is expected to decline, potentially causing a low flow. To test whether precipitation minima are driving annual low flows, we identify periods of the annual lowest precipitation. We define this as the annual minimum of the precipitation sum over the previous 30 days.

2.3.2. Excess Potential Evapotranspiration

Annual low flows may occur after periods of high excess potential evapotranspiration (excess PET). We define high excess PET as the annual maximum of the sum of potential evapotranspiration PET minus precipitation P over the previous 30 days. This definition is chosen because streamflow should decline as catchment storage decreases, and thus should decline whenever evapotranspiration exceeds precipitation. We use PET as a proxy for actual evapotranspiration (AET) because it can be readily calculated for large numbers of catchments, although it will overestimate AET where soil moisture is limiting. We also neglect discharge as part of the water balance because, for the study catchments, PET is on average at least five times larger than discharge during summer low-flow periods. Thus, in this simplified framework, we expect streamflow to decrease whenever PET exceeds P .

2.3.3. Low Air Temperature

At high elevations or northern latitudes, streamflow can be affected by low air temperatures that freeze precipitation and inhibit snowmelt, thus limiting recharge and potentially causing low flows. As a potential low-flow driver, we calculate the annual minimum of the average air temperature over the previous 30 days, although we recognize that low flows may occur after extended periods of subfreezing temperatures, rather than briefer, colder periods (e.g., Van Loon et al., 2015). Because our hypothesized mechanism requires subfreezing temperatures, we exclude annual low temperatures above 0°C as potential low-flow drivers. Freezing temperatures do not lead to complete cessation of streamflow in any of our study catchments.

3. Results and Discussion

3.1. Seasonality of Low Flows Across Europe and the US

The timing of annual low flows varies regionally across continental Europe and the contiguous United States (Figure 1). Some regions have distinct late-summer low flows (typically occurring in August through

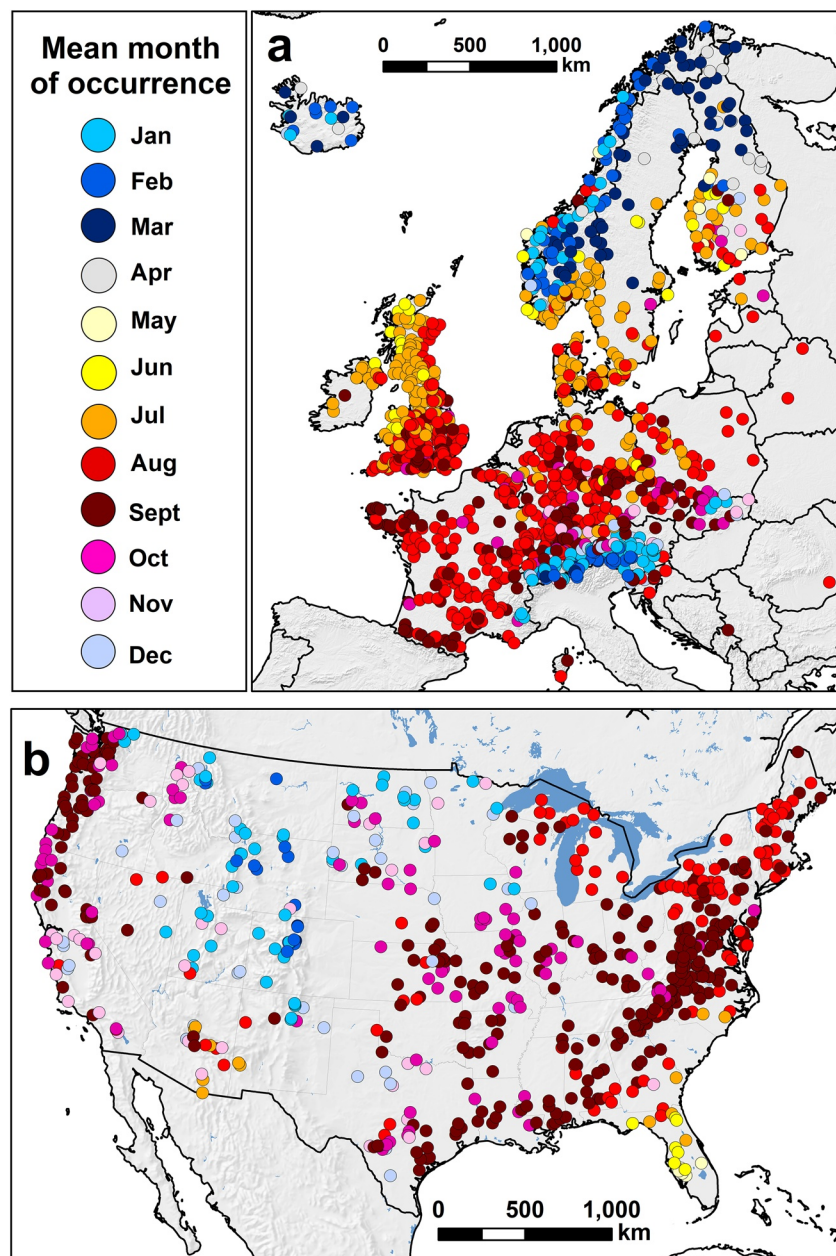


Figure 1. The mean date of occurrence of annual low flows varies regionally across Europe (a) and the continental US (b). Most low flows occur in the late summer and autumn months, but low flows tend to occur during the winter months in some regions (Scandinavia and the Alps in Europe, and the Rocky Mountains and Upper Midwest in the US).

October) while others have distinct winter low flows (typically occurring in December through February). Very few catchments have low flows that occur in the period April through June (Figure 1). Similar distinct summer and winter low flows have been reported for regions within Europe (e.g., Demirel et al., 2013; Laaha & Blöschl, 2006b; Tongal et al., 2013; Van Loon et al., 2015; Wehren et al., 2010) and for parts of the US (e.g., Cooper et al., 2018; Dierauer et al., 2018; Pournasiri Poshtiri et al., 2019).

In most of continental Europe, annual low flows tend to occur during late summer and early autumn (mostly during August and September). For example, low flows typically occur during August in most of continental Europe north of the Alps. In most of the United Kingdom and southern Scandinavia, low flows tend

to occur slightly earlier, during July or even June. In northern Scandinavia and the Alps, by contrast, low flows tend to occur during the coldest months of the year. Throughout the central Alps (mainly in catchments in Austria, Switzerland and south-eastern France), most low flows typically occur in January and February, whereas in Scandinavia they also occur in March and April (e.g., Finland).

In the United States, summer and autumn low flows typically occur slightly later than in Europe, with more than half of the US catchments having typical low flows in September. Low flows typically occur in September in much of the eastern US, in August in the northeast, and in June in Florida. In the central US states of Indiana, Illinois, and Missouri, and in the southern part of California, low flows occur slightly later, primarily in October with some also in September or November. In the northern part of the West Coast, low flows tend to occur in September and October. By contrast, annual low flows occur during winter in parts of the Rocky Mountains, the upper Midwest and the Plains states. For example, in North Dakota, Iowa and Minnesota, low flows tend to occur in November through January, and in higher elevation catchments of the Rocky Mountains, low flows typically occur during January and February. Across both continents, winter low flows occur almost exclusively in areas where winter temperatures tend to drop far below 0°C (e.g., the European Alps, Scandinavia, the Rocky Mountains, and the northern part of the US Midwest).

The consistency of low-flow timing also varies between regions (Figure 2). Low-flow timing is relatively consistent from year to year in most European catchments and especially in the contiguous United States, as indicated by consistency values often approaching one (e.g., $F > 0.6$ in 75% and 82% of the European and US catchments, respectively), as indicated by the green dots in Figure 2. Nevertheless, low-flow seasonality can be highly variable in particular regions of Europe and the US. In Europe, highly variable low-flow timings ($F < 0.4$) are found, for example, in parts of Scandinavia (i.e., central Finland) and in some mid-elevation catchments northeast of the Alps (Figure 2a). Similarly, the timing of low flows is variable in parts of the US Midwest, with F sometimes below 0.4. In these locations, annual low flows switch between winter and summer, presumably reflecting year-to-year differences in the importance of winter freezing versus summer warm, dry conditions as drivers of low flows, respectively. However, even in these catchments with variable low-flow timing, annual low flows still mostly occur in either winter or late summer/early fall, rather than in the shoulder seasons.

Catchments where low flows typically occur during late summer (August and September) or late winter (February and March) tend to have a more consistent timing compared to catchments where low flows typically occur during other times of the year. In places with consistent seasonal timings, the drivers of these low flows are likely to be most strongly connected to the periodic seasonal climatic regime. For example, for catchments that have their low flows during winter, the drivers of these low flows are generally related to freezing temperatures. Consistent freezing temperatures will almost never occur outside the winter low-flow period. Low flows in the shoulder seasons are more likely to occur as the result of different mechanisms in different years, which are expected to be more variable in their timing. In addition, the weaker link of those low flows with a distinct season makes them more likely to result from shorter term weather conditions, rather than the longer term seasonal climatic regime.

3.2. Effects of Dams and Reservoirs on Low-Flow Seasonality

Streamflow in the studied catchments can be substantially influenced by human activity, such as water abstraction and water storage in reservoirs, which may influence low flows. To test the effect of reservoirs on the seasonality of low flows, we selected 33 catchments for which reservoir locations and construction dates were available (see Table S1) and calculated the low-flow timing before and after reservoir construction (Figure 3a). In almost all catchments (30 out of 33) the mean low-flow timing changed by less than one month. Such small changes in timing can also be caused by natural variations rather than human water use. To test for this possibility, we also calculated changes in the timing of low flows in 33 randomly chosen catchments without reservoirs, with each record split in half. Comparing Figures 3a and 3b indicates that the changes in low-flow timing in the catchments with no major reservoirs resemble the changes in low-flow timing before and after reservoir construction. This suggests that reservoirs will typically have a small influence on the seasonal timing of annual minimum flows across our study sites, although they may affect the magnitude of those flows. This finding is consistent with previous studies which determined that low-flow timing is more strongly controlled by climate than by human activities in US and Swiss catchments

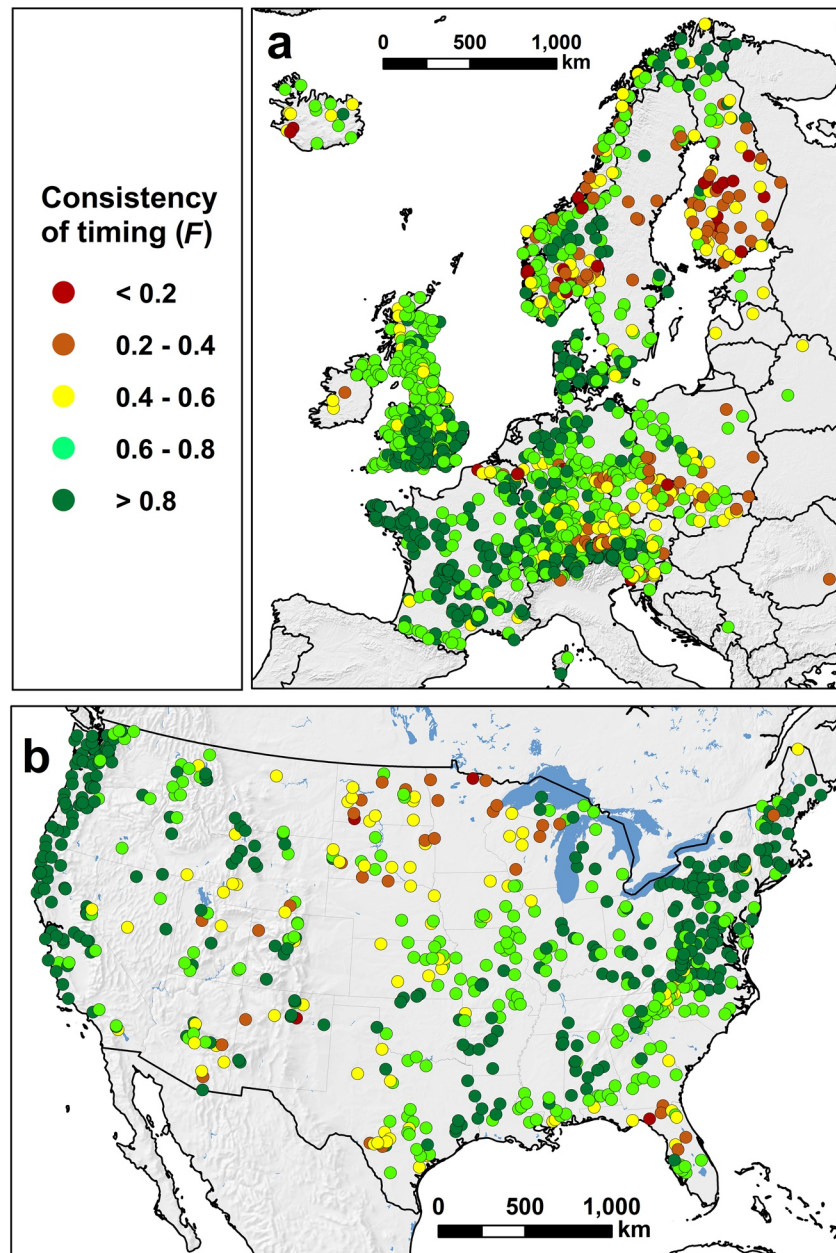


Figure 2. The consistency in the date of occurrence of annual low flows varies regionally across Europe (a) and the continental US (b). Low-flow timing is less consistent (low F) in the US Midwest and parts of Scandinavia, compared to the more consistent (high F) low-flow timing in most other regions.

(Ferrazzi et al., 2019; Floriancic et al., 2020; Sadri et al., 2016). We caution the reader that this analysis is not comprehensive as it was only done for 33 catchments where we had information on the timing of dam construction. It is possible that dam effects on streamflow seasonality are more pronounced in other regions. However, although reservoirs could significantly affect low-flow timing in individual catchments, as long as such impacts are relatively rare (as is indicated by our analysis), they should have little effect on regional patterns that are inferred across many catchments. For example, distinct regional patterns are evident in Figure 1, despite potential human influences on flow regimes at many sites across both Europe and the US. Such patterns would be unlikely if human influences dominate low-flow seasonality.

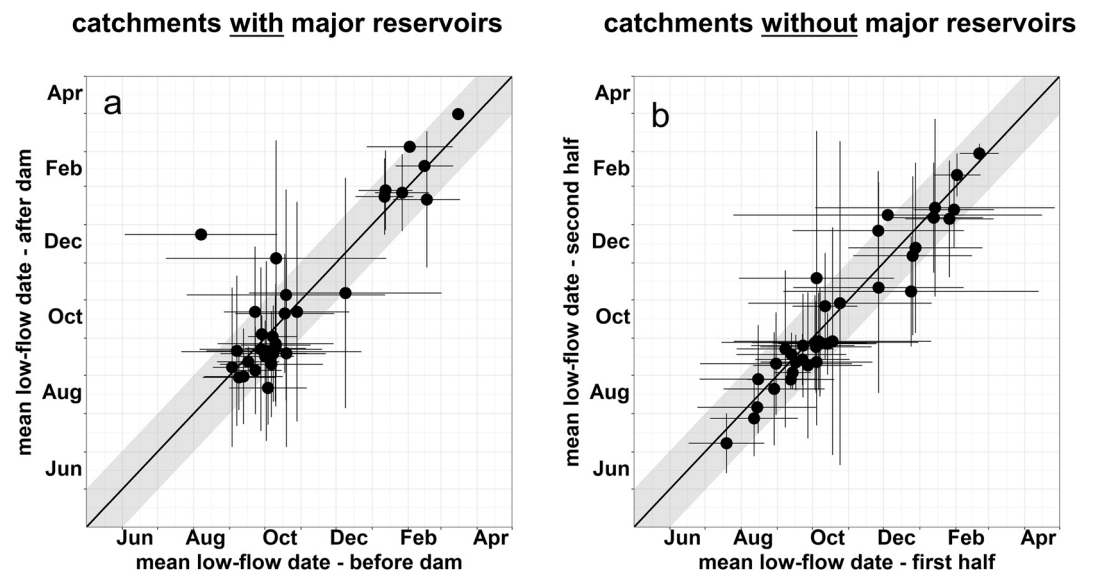


Figure 3. The mean timing of low flows (black dots) before and after reservoir construction for 33 catchments with major reservoirs (a) and for 33 randomly selected catchments without major reservoirs (b). The error bars indicate the standard deviation of the timing (Young et al., 2000) before (x-axis) and after (y-axis) reservoir construction (a) and for the first and second halves of timeseries from catchments without reservoirs (b). The gray shading indicates a one-month interval around the 1:1 line. In general, seasonality changes appear comparable in catchments with and without reservoir construction.

3.3. The Timing of Potential Climatic Drivers of Low Flows

To assess the drivers of low flows across Europe and the contiguous US, we first mapped the mean months of lowest precipitation (Figures 4a and 4b), highest excess *PET* (Figures 4c and 4d) and lowest temperatures (Figures 4e and 4f) across the two continents. We then identified sites where each of these annual climatic extremes was a plausible driver of low flows, by assessing their temporal correspondence with the timing of the annual low flow at each site.

The seasonality of annual minimum precipitation varies regionally across the continents. In central Europe (Figure 4a), precipitation minima generally occur in January and February. They usually occur in March through May in Scandinavia and slightly later in the United Kingdom and Iceland. In western France, precipitation minima typically occur in the summer months (July and August). In the US (Figure 4b), precipitation minima typically occur in January and February in the Midwest, Northeast and Florida, in August through November along the West Coast (with later minima in the southwest than the northwest), and during August through October in the Southeastern states of Kentucky, Tennessee, Mississippi, Alabama, and Georgia. Some regions with Mediterranean climates, including parts of the US West Coast and southern Europe, experience several months of low precipitation in summer and autumn.

Excess potential evapotranspiration typically peaks in midsummer in Europe and the US. In Europe (Figure 4c), annual maxima of excess *PET* typically occur in July (Scandinavia, northern United Kingdom, and Eastern Europe) and August (in the southern United Kingdom and France). Across the US (Figure 4d), the months of maximum excess *PET* range from May and June (in Florida) to July (across most of the continent) and August (in parts of Texas and the Southeastern states of Kentucky, Tennessee, Mississippi, and Alabama).

The lowest annual temperatures almost exclusively occur during January and February across Europe (Figure 4e) and the US (Figure 4f). The lowest temperatures typically occur in January in the US, and in February across Europe.

The consistency of the timing of lowest precipitation varies regionally (Figures 5a and 5b). The timing of precipitation minima is most consistent along the US West Coast and in the central parts of the US. Precipitation minima have larger year-to-year variability along the East Coast and in the southeastern states.

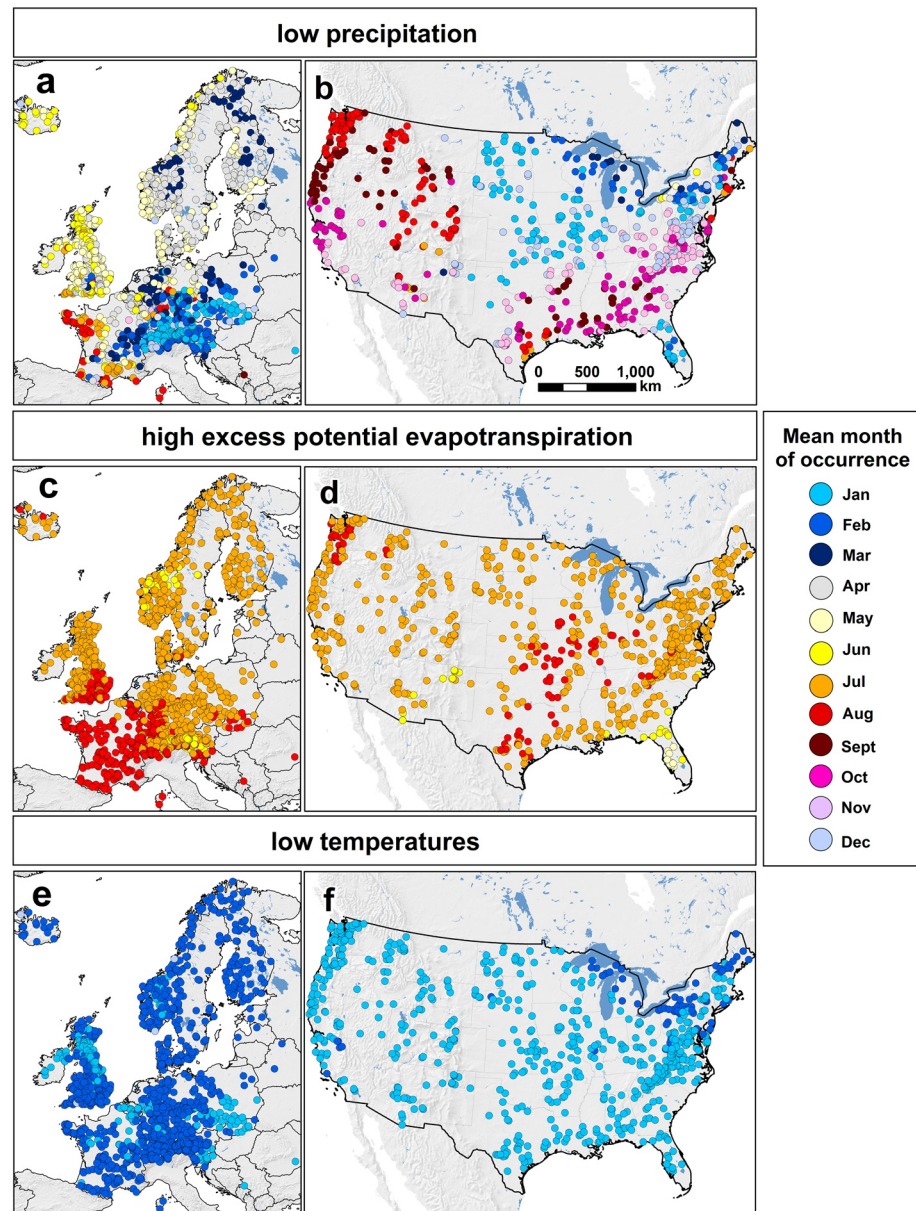


Figure 4. The average timing of potential climatic drivers of low flows across Europe and the US, indicating the mean months of lowest precipitation (a and b), highest excess potential evapotranspiration (c and d) and lowest temperature (e and f).

Across Europe, precipitation minima are most consistent across the Alps and in parts of Scandinavia and Iceland, and less consistent across most of continental Europe and the southern United Kingdom. In general, the timing of annual minimum precipitation (Figures 5a and 5b) is much less consistent than the timing of annual lowest flows (Figure 2). This suggests that many annual low flows are not exclusively driven by annual precipitation minima. The timing of highest excess PET is highly consistent across almost all of Europe and the US. Slightly lower consistencies are observed across the European Alps, as well as in the southeastern parts of the US (Figures 5c and 5d). The timing of lowest temperatures is highly consistent across almost all of Europe and the US (Figures 5e and 5f).

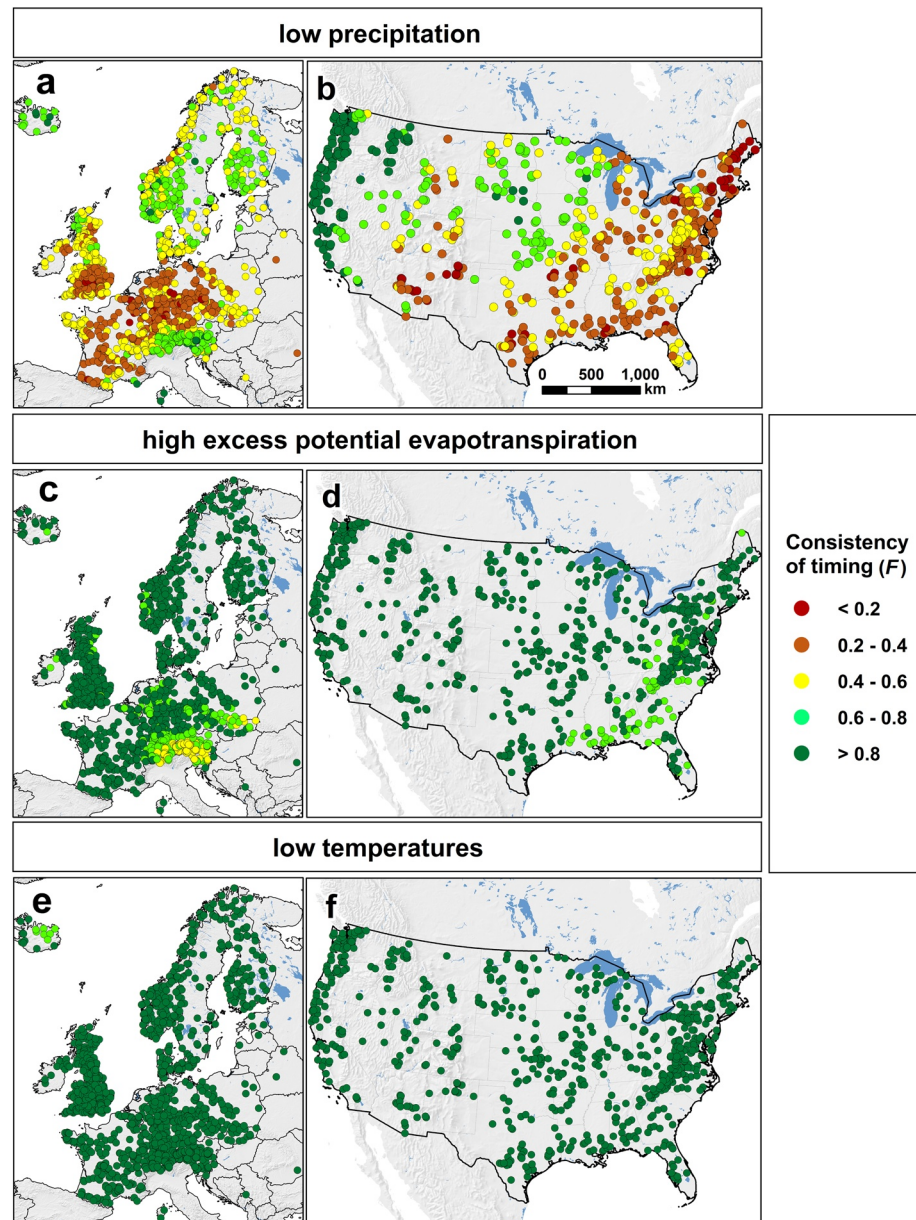


Figure 5. Consistency of the timing of potential climatic drivers of low flows across Europe and the US, indicating the consistency of the mean months of lowest precipitation (a and b), highest excess potential evapotranspiration (c and d) and lowest temperature (e and f) during the year.

3.4. Similarities in Timing Between Annual Low Flows and Climatic Drivers

The main climatic drivers of low flows across Europe and the United States can be inferred by comparing their annual timing with the timing of low flows. We consider annual climatic extremes to be plausible drivers of low flows at any given site if they coincide with annual low flows (within plus or minus 30 days) more frequently than expected by chance, as described in Section 2.3. At most of the gauges across Europe and the US, where 34 years of records are available, the p -values of 0.05, 0.01, 0.001, and 0.000015 correspond to 10, 12, 14, and 17 years with coincident timing of the lowest annual flow and at least one of the candidate drivers.

Low flows in 89% of the European catchments, and 86% of the US catchments, exhibit statistically significant ($p < 0.05$) overlap in timing with at least one potential climatic driver (Figure 6), with strong regional

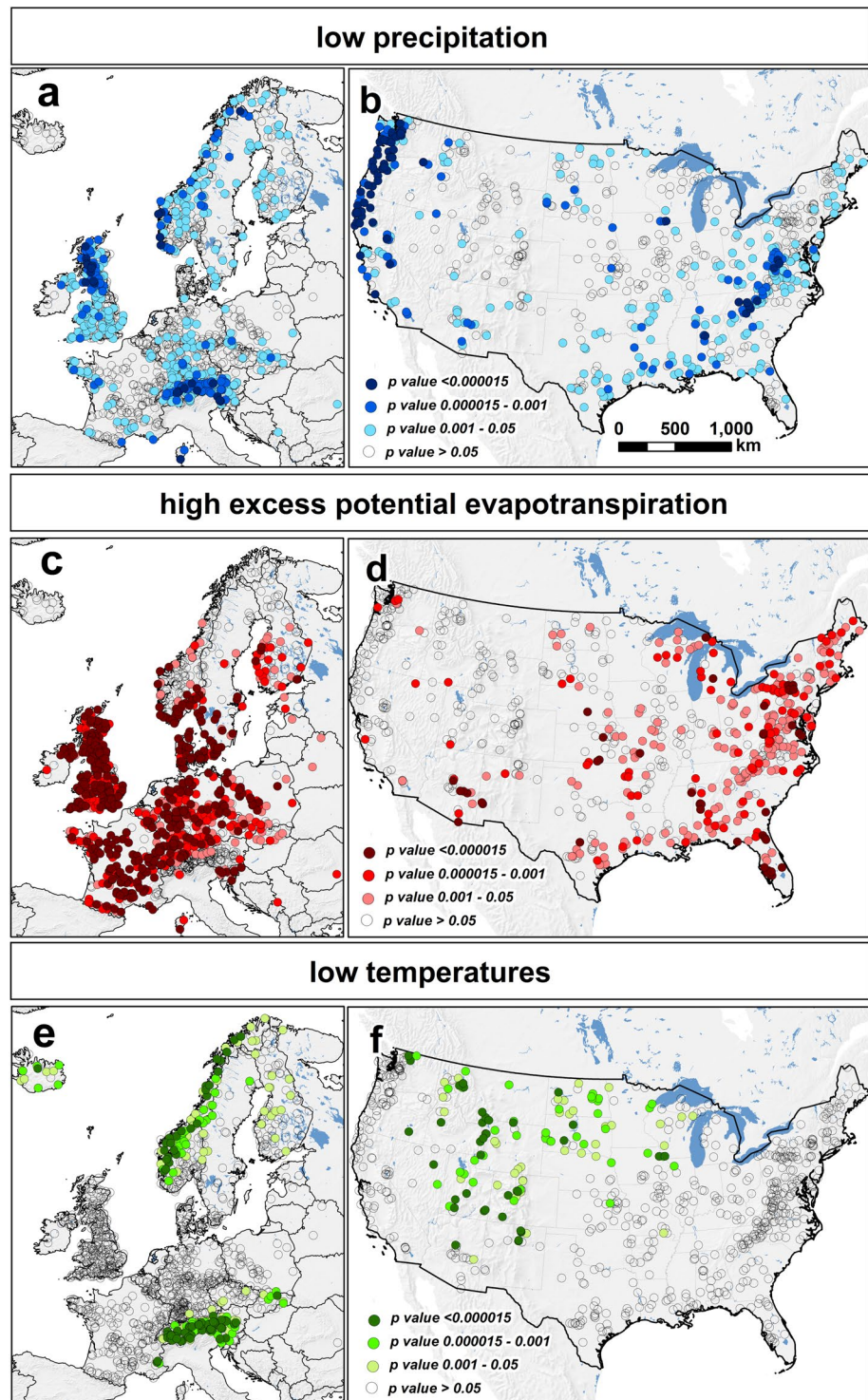


Figure 6. Similarities in timing between annual low flows and three climatic drivers (annual minimum precipitation, maximum excess potential evapotranspiration, and minimum temperature), mapped across Europe (a, c, and e) and the US (b, d, and f). Colored markers indicate sites where annual low flows occur within ± 30 days of the given driver significantly more often than expected by chance, as quantified by the p -values. Sites exhibiting no statistically significant association with any driver ($p > 0.05$ for all three drivers) are mapped in Figure S3, and sites with statistically significant associations ($p < 0.05$) with multiple drivers are mapped in Figure S4.

differences in which drivers overlap (and are therefore considered as plausible low-flow drivers). Low flows overlap with the timing of lowest precipitation in 40% of the European catchments and roughly 49% of the US catchments (Figures 6a and 6b). Low precipitation coincides with low flows in Europe across the Alps, in the United Kingdom and in parts of Scandinavia. In the US low precipitation is a potential driver of low flows along the West Coast and across parts of the southeastern states (where, however, the consistency of the timing of precipitation minima is low; see Figure 5b).

High excess *PET* is a plausible driver of low flows in 67% of the European catchments and 47% of the US catchments ($p < 0.05$). Low flows overlap with high excess *PET* in most of Central Europe north of the Alps, except for northern Scandinavia and Iceland. In the US, high excess *PET* is a potential driver of low flows in many catchments along the East Coast and Gulf Coast, and scattered catchments elsewhere (Figures 6c and 6d). The prevalence of excess *PET* as a plausible low-flow driver shows that catchment drying is often not caused by low precipitation alone, but by precipitation that is substantially exceeded by evaporative demand (e.g., Mastrotheodoros et al., 2020; Seneviratne et al., 2012; Teuling et al., 2013). Thus, low flows occur in late summer and fall across large parts of Europe and the US (Figure 1), although these seasons often do not coincide with the periods of lowest precipitation (Figures 4a and 4b).

We must be cautious in attributing low flows to high *PET*, however, because not only can high *PET* lead to drying (by increasing actual evapotranspiration), but drying can also lead to high *PET* (due to higher temperatures that result from greater partitioning of energy to sensible rather than latent heat when soil moisture is low). Thus periods of low precipitation can also lead, through drying, to periods of high *PET*. The role of *PET* in drying a catchment could thus be overestimated, especially in water-limited environments. For example, Mastrotheodoros et al. (2020) used Alpine-scale ecohydrological modeling to show that actual evapotranspiration in an exceptionally dry summer can be high and close to *PET* at high altitudes where *ET* is energy limited, leading to less runoff, while actual evapotranspiration may decrease well below *PET* at lower altitudes, where *ET* is water limited.

Low temperatures are a plausible driver of low flows in 23% of the European catchments and 17% of the US catchments ($p < 0.05$). Low flows overlap with the timing of lowest temperatures across the Alps, in Norway and Finland, and in the Rocky Mountains and Upper Midwest and Plains states of the US (Figures 6e and 6f).

As described in Section 2.3 above, we can also statistically *exclude* individual drivers where their climatic extremes coincide with low flows much *less* often than expected by chance. As Figure 7a and 7b show, this occurs for low precipitation at only a few widely scattered sites (comprising 4% and 3% of European and US sites, respectively). Because we would expect some sites to exhibit statistically significant results (e.g., 2% of sites at $p < 0.02$) even if the null hypothesis were true, we do not have a strong evidence that excludes low precipitation as a plausible low-flow driver in any region. This is a nearly inevitable result of the fact that precipitation minima exhibit much less year-to-year consistency than low flows do. Extreme drought years are likely to be associated with low flows at many sites, even where precipitation minima are not the drivers of typical low flows. Nonetheless these extreme drought years will preclude the statistically significant lack of overlap (33 or 34 out of 34 years; see Section 2.3) that would be necessary to exclude precipitation minima as drivers.

By contrast, Figures 7c and 7d show that we can exclude high excess *PET* as a plausible low-flow driver in the Alps and in Norway, (northern) Finland, and Iceland, as well as in much of the Intermountain West and the Pacific Coast of the US. Comparing Figures 7a and 7d with Figures 6c and 6d, we note that at many sites (83% and 69% of European and US sites, respectively), we can either confirm or exclude high excess *PET* as a low-flow driver with high statistical confidence, because less than one-third of the sites yield statistically inconclusive results. Consequently, Figures 6c, 6d, and 7d show that in most regions where high excess *PET* cannot be confirmed as a low-flow driver, it can be excluded with high confidence, and vice versa.

We can exclude low temperatures as plausible low-flow drivers across most of continental Europe north of the Alps, southern Scandinavia, and the United Kingdom, as well as most of the Eastern US and the Pacific Coast (Figures 7e and 7f). This result is not surprising for many of these sites, where winter temperatures rarely dip below zero for extended periods. However, we note that we can also exclude low temperatures as low-flow drivers in the Northeastern US and New England, where sub-zero temperatures are common

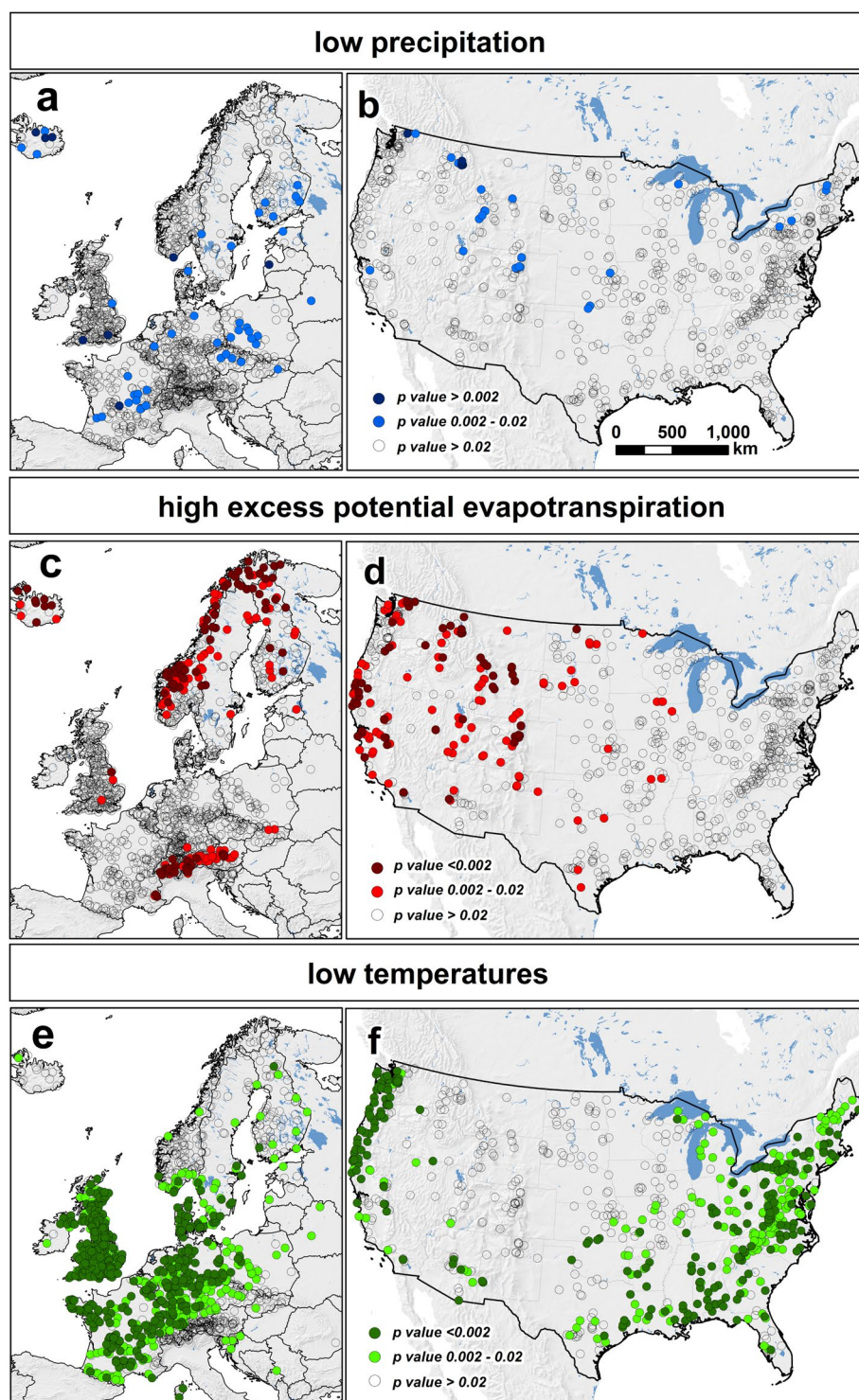


Figure 7. Sites where annual climatic extremes can be statistically excluded as potential drivers of low flows, because they overlap in time much less frequently than expected by chance, mapped across Europe (a, c, and e) and the US (b, d, and f). Colored markers indicate sites where annual low flows occur within ± 30 days of the given driver significantly less often than expected by chance, as quantified by the associated p -values derived from binomial statistics (see Section 2.3 for details).

during the winter. Comparison of Figures 7e and 7f with Figures 6e and 6f show that low temperatures can be either confirmed or excluded as low-flow drivers at nearly all sites (81% and 78% of European and US sites, respectively) with high statistical confidence, because only about 20% of the sites yield statistically inconclusive results. Consequently, Figures 6e, 6f, and 7f show that in regions where low temperatures cannot be confirmed as low-flow drivers, they can be excluded with high confidence, and vice versa.

The percentages reported above reflect the prevalence of plausible low-flow drivers among our study catchments. Extrapolating these percentages to all of Europe or all of the US should be done with caution, because some regions and catchment sizes are under-represented in our data set, and others are overrepresented. In some regions, multiple potential drivers coincide, making their relative importance difficult to determine. In the Alps, for example, low flows overlap with the periods of lowest temperatures, but also with lowest precipitation. Similarly, in the eastern US and most of the United Kingdom, low flows overlap both with periods of low precipitation and with periods of high excess *PET*.

3.5. Broader Implications of the Findings

The observed patterns of low-flow seasonality can help in anticipating how low flows may respond to changes in climate. Low flows generally occur during distinct times of the year (mostly in late summer and winter). While model projections indicate that the magnitudes of low flows can substantially change in the future (e.g., Marx et al., 2018), shifts in low-flow timing are much less likely in most cases. This is because, although low-flow magnitudes are likely to change continuously with the strengthening or weakening of their associated drivers (and thus shifts in the water balance), low-flow timing can change substantially only when there is a switch from one regime (e.g., cold temperatures with winter low flows) to another (e.g., high *ET*). As a result, the distinction between pronounced summer low-flow regimes and winter low-flow regimes can be expected to largely remain unaltered in the future; thus while the climate warms, the two main low-flow regimes will likely persist. Distinct changes for one regime to another would be expected only in catchments that are at the (temperature) threshold between these two regimes. However, this will not be a hard transition from one to another but will rather mean more variable annual low-flow timings, with less consistency throughout the years.

Summer and winter low flows also occur with high consistency (i.e., *F*-values approach 1 — Figure 2). This consistent low-flow seasonality across most of Europe and the US contrasts with the more variable seasonal timing of precipitation minima (Figure 5), suggesting that low flows may often be decoupled from precipitation minima. For example, low flows exhibit high seasonal consistency ($F > 0.6$) across most of the eastern US and much of Europe, where precipitation minima generally exhibit much lower seasonal consistency ($F < 0.4$). This disconnect between the timing of precipitation minima and low flows suggests that even if precipitation seasonality shifts with climate warming, the timing of summer low flows may in many cases remain largely unaffected. This result is not universal, however, because in some regions (such as the Pacific Coast of the US), precipitation minima and low flows exhibit strong, and overlapping, seasonality.

Our analysis indicates that many low flows are driven either by low winter temperatures (leading to freezing) or high summer temperatures (leading to high excess *PET*). Rising temperatures are affecting hydrological regimes globally. Climate warming can be expected to raise both winter temperatures (thus reducing the likelihood of low flows due to freezing) and summer temperatures (thus increasing the likelihood of low flows due to high excess *PET*). Across most of Europe and the US we expect that effects on low flows will be primarily driven by changes in temperature (and strongly associated with *ET*), but in catchments with winter low flows, the effects of rising temperatures on low flows will be primarily driven by changes in snow accumulation and melt. Rising summer temperatures are likely to be associated with an increase in soil water deficits and could lead to lower flows (e.g., Mastrotheodoros et al., 2020; Teuling et al., 2013), but not substantially shift low-flow timing, since the warmest temperatures and thus the highest excess *PET* will still likely occur in mid to late summer.

By contrast, rising winter temperatures are likely to shorten winter freezing periods, and thus lead to higher low flows, at sites that remain cold enough that their low flows still occur during winter. But at some sites in transitional altitudes and latitudes (e.g., the Alpine foothills or parts of southern Scandinavia), low flows that were driven by winter freezing in the current climate may instead be driven by summer *PET* in

a warmer future climate, leading to dramatic shifts in low-flow timing. On the other hand, an increase in winter temperatures will most likely increase the proportions of liquid (rain) and solid (snow) winter precipitation, increasing streamflow magnitudes in winter.

4. Summary and Conclusions

We analyzed regional patterns in the timing of annual low flows across 1860 catchments in Europe and the contiguous United States. Low flows tend to occur in either late summer/autumn or winter across these study regions, with relatively few low flows falling outside these two seasons (Figure 1). In Europe, winter low flows primarily occur in the Alps and northern Scandinavia, while in the United States, they primarily occur in the northern Rocky Mountains and the Upper Midwest and Plains states. In the remainder of the European and US sites, annual low flows occur almost exclusively in late summer (Figure 1). In most of the European catchments, summer low flows tend to occur in August and September, while in the US catchments, low flows occur mostly in September. In all regions, there is typically strong year-to-year consistency in the timing of both summer and winter low flows (Figure 2), whereas low flows that occur during other seasons are less consistent from year to year. Although many catchments across Europe and the US are influenced by dams and reservoirs, our analysis of low-flow timing before and after reservoir construction suggests that they do not strongly affect the seasonality of low flows (Figure 3).

Across Europe and the US, low flows can be objectively linked to three distinct climatic drivers: low precipitation, high excess *PET*, and low temperature (Figure 6). Warm-season low flows are primarily associated with periods of high excess *PET*, whereas cold-season low flows are primarily associated with subfreezing temperatures. The timing of annual precipitation minima exhibits greater regional variability (Figure 4) and greater year-to-year variability (Figure 5) than the timing of either annual excess *PET* maxima or temperature minima. Precipitation minima can overlap with both warm-season and cold-season low flows. However, the timing of precipitation minima is typically much more variable than the timing of the low flows themselves, suggesting that precipitation minima are not necessarily the drivers of all of those low flows. Low flows in 89% of the European catchments, and 86% of the US catchments, exhibit statistically significant ($p < 0.05$) overlap in timing with at least one potential climatic driver (Figure 6). Conversely, in some regions we can statistically exclude certain climatic extremes as potential low-flow drivers (Figure 7). By quantifying the timing and year-to-year consistency of low flows and their potential climatic drivers, our analysis reveals which climatic extremes are (and are not) the likely causes of low flows across different regions of Europe and the US.

Data Availability Statement

All data for the US catchments were obtained from the CAMELS data set. <https://ral.ucar.edu/solutions/products/camels> Discharge data for Europe were obtained from the GRDC database. <https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#> Mean catchment temperatures and precipitation were extracted from E OBS. https://www.ecad.eu/utills/mapserver/eobs_maps.php.

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