
HYDROCLIMATIC CHANGE REORGANIZES KARST SPRING DISCHARGE IN THE ALPINE REGION ACROSS DISCHARGE REGIMES AND KARST-SYSTEM PROPERTIES

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ABSTRACT

Karst springs are important water resources for the Alpine region and are particularly sensitive to hydroclimatic change due to their comparably short response times. Yet how their hydroclimatic responses differ among discharge regimes and karst systems with different storage properties remains poorly understood. We analyzed 85 karst springs across the wider Alpine region over 2003–2022 to assess how recent trends in discharge, precipitation, and temperature vary across (i) contrasting discharge regimes and (ii) karst-system response types. To this end, we performed clustering based on discharge seasonality and derived three response types using an established karst-system classification framework. Trends in annual, seasonal, and monthly hydrometeorological variables, as well as in the magnitude and timing of low and high flows, were assessed using the modified Mann–Kendall test and Sen’s slope estimator. Results showed that seasonal flow redistribution was more pronounced than annual discharge change, with widespread increases in winter discharge. Responses differed strongly among the four identified discharge regimes. Winter-pluvial springs in the peri-Alpine region tended toward decreasing spring and summer discharge and increasing winter discharge, resulting in increasing seasonality, with these changes largely associated with precipitation trends. Low and high flows showed corresponding changes, with decreasing low-flow and increasing high-flow magnitudes. In contrast, snow-influenced springs in the core Alpine region showed decreasing seasonality, characterized by mostly increasing winter discharge and decreasing summer discharge, consistent with reduced snow storage and earlier snowmelt. Low-flow magnitudes generally increased, and low-flow occurrence shifted earlier. Thus, these contrasting seasonal shifts suggest that winter water-availability constraints may be reduced in the core Alpine region, whereas reduced summer discharge may increasingly constrain water availability in

the peri-Alpine region. Discharge trend patterns were more clearly structured by discharge regime than by karst-system properties. However, trend magnitudes and variability among springs generally decreased from faster- to slower-responding systems. Overall, karst springs in the wider Alpine region respond clearly but heterogeneously to hydroclimatic change, highlighting their value as regional climate indicators and the need for sustained long-term monitoring.

1 Introduction

The European Alps span pronounced climatic gradients and a broad elevation range, encompassing hydrological regimes that differ in the relative importance of rainfall, snowmelt, and glacier melt (Bard et al., 2015). Climate warming alters the main controls of these regimes, including precipitation seasonality and intensity, rain–snow partitioning, seasonal snow storage, glacier mass balance, and atmospheric evaporative demand (Gobiet et al., 2014; Kotlarski et al., 2023; Beniston et al., 2018). Because these controls vary strongly with elevation, discharge from Alpine catchments integrates potentially contrasting hydrological responses across their elevation ranges.

Impacts of changing climatic conditions on Alpine streamflow have been extensively studied over the past decades. Observed streamflow changes are generally more coherent at seasonal than at annual scales (Stahl et al., 2010; Kormann et al., 2015; Bard et al., 2015). Rising temperatures shorten the snow accumulation period, reduce seasonal snow storage, and advance snowmelt (Beniston et al., 2018; Matiu et al., 2021). A larger fraction of cold-season precipitation falling as rain, together with earlier meltwater contributions, generally increases winter and early-spring runoff, alleviates winter low flows in snow-dominated catchments, and advances snowmelt-driven high flows, while earlier depletion of seasonal snow storage reduces meltwater contributions later in the year and advances the seasonal recession (Stahl et al., 2010; Bard et al., 2015; Blöschl et al., 2018; Kormann et al., 2015). Increased evaporative demand can further intensify summer low flows, particularly in lower-elevation catchments (Duethmann and Blöschl, 2018; Muelchi et al., 2021a). Climate projections indicate that this seasonal redistribution will intensify during the 21st century (Hanus et al., 2021; Brunner et al., 2019; Muelchi et al., 2021a,b), with implications for drinking water supply, hydropower, agriculture, tourism, and aquatic and terrestrial ecosystems, both within the Alps and in downstream lowlands (Viviroli et al., 2011; Beniston et al., 2018; Dumont et al., 2025).

Compared with streamflow, climatic effects on Alpine groundwater have been investigated less systematically, although groundwater contributes substantially to streamflow in many high mountain regions, particularly during low-flow periods (Somers and McKenzie, 2020). Springs constitute natural discharge points at the interface between groundwater and surface water and are commonly less directly affected by anthropogenic influences than surface-water systems. Their hydrographs integrate the effects of climate-driven recharge with aquifer-specific storage and drainage processes, thereby providing valuable observation points for assessing groundwater responses to hydroclimatic variability (Kresic and Bonacci, 2010). With exposed carbonate rocks covering approximately 40% of the Alps, karst aquifers represent a major water resource and supply drinking water to both local communities and major cities such as Vienna and Innsbruck (Goldscheider et al., 2025). Karst areas in the Alps, particularly at high elevations, are often characterized by thin or discontinuous soil cover and highly permeable infiltration pathways that facilitate rapid infiltration (Chen et al., 2018). Together with high precipitation and relatively low evapotranspiration, these characteristics can contribute to substantial groundwater recharge (Goldscheider et al., 2025). Groundwater flow occurs through hydraulically heterogeneous and interconnected matrix, fracture, and conduit pathways (Ford and Williams, 2007b), and the resulting discharge dynamics are commonly conceptualized as comprising quickflow and baseflow components (e.g., Mangin, 1975). Many karst systems in the Alps are characterized by steep hydraulic gradients and well-developed conduit networks that facilitate rapid drainage, potentially increasing their sensitivity to changing climatic conditions (Fiorillo et al., 2021; Chen et al., 2018). However, differences in the degree of karstification and the complex geological and tectonic setting of the Alps contribute to substantial variability in aquifer storage and drainage behaviour, resulting in contrasting spring discharge dynamics (Goldscheider et al., 2025; Hartmann et al., 2014). Because of their pronounced spatial heterogeneity and complex flow dynamics, karst studies have commonly focused on individual systems, while systematic regional comparisons of karst-system responses remain limited. Consistent datasets of karst spring hydrographs can help bridge this gap, as indicators of recharge dynamics and aquifer properties can be derived directly from the hydrographs (Kresic and Bonacci, 2010; Joger et al., 2026a).

Giese et al. (2025) first assessed long-term hydrometeorological trends across a larger number of European karst springs. They evaluated 54 springs over a 20-year period and a subset of 22 springs over 40 years, mostly located in France and Great Britain. Discharge trends were spatially heterogeneous and mostly non-significant. Winter discharge trends were predominantly positive, whereas the most coherent signal was a decrease in autumn precipitation accompanied by decreasing autumn discharge. Overall, no clear relationship between discharge trends and the storage-related characteristics of the assessed karst systems was identified. For the Austrian Alps, Vremec et al. (2025) analyzed hydrometeorological trends for 27 springs over the period 1997–2022, including 19 karst springs. Trends were evaluated for four spring groups previously identified through clustering of discharge seasonality and autocorrelation (Seelig et al., 2024). Annual discharge trends were generally weak, whereas increasing winter discharge and increasing low flows were observed across most springs. Fast-responding karst springs in the Northern Calcareous Alps showed the clearest seasonal redistribution, with earlier timing of low flows and high flows and decreasing spring and summer flows, resulting in reduced seasonality. These changes were mainly linked to warming-induced shifts in rain–snow partitioning and snowmelt timing.

However, a systematic assessment of hydrometeorological trends across karst springs in the wider Alpine region based on consistently preprocessed data is still lacking. In particular, it remains unclear how seasonal discharge changes differ among contrasting discharge regimes and to what extent karst system storage and drainage characteristics are reflected in these trends. Such a regional assessment is important to better understand spring discharge responses across the pronounced elevational and hydroclimatic gradients of the Alps.

To address these gaps, this study analyses hydrometeorological trends for 85 karst spring catchments within the ALPAKAS dataset across the wider Alpine region, defined here as the area covered by the EU Strategy for the Alpine Region (EUSALP), over the 20-year reference period 2003–2022. The analysis considers trends in annual and seasonal mean discharge, as well as in annual indicators of low-flow and high-flow magnitude and timing, and evaluates differences among discharge regimes and karst-system properties. Particular emphasis is placed on examining regime-specific hydroclimatic controls on seasonal flow redistribution by relating monthly precipitation and temperature trends to corresponding trends in discharge and Pardé coefficients. Specifically, we address the following research questions: (i) What trends occur in annual mean discharge, seasonal discharge, and the magnitude and timing of low flows and high flows across karst springs in the Alpine region? (ii) How do discharge trends vary among discharge regimes and how are they related to changes in precipitation and temperature? (iii) How do discharge trends differ among karst springs with contrasting storage and drainage characteristics?

2 Data and methods

2.1 Hydrometeorological time series

All hydrometeorological time series analyzed in this study were obtained at daily resolution from the publicly available ALPAKAS dataset (Joger et al., 2026b). ALPAKAS contains 243 harmonized karst spring hydrographs of varying record periods across the EUSALP area, together with meteorological variables aggregated at catchment scale. Karst spring hydrographs in ALPAKAS were subject to thorough quality control through a combination of manual inspection and automated methods. This included the flagging of outliers and artefacts, as well as the identification of periods affected by artificial influences using changepoint analysis, as described in detail in Joger et al. (2026a). These quality-flagged data points and time series segments were removed prior to analysis.

To ensure comparability among sites, a 20-year reference period was defined, covering the hydrological years (1 October – 30 September) 2003–2022. Missing values were not interpolated or imputed to avoid introducing artificial values that may affect variability, extremes, and serial dependence. Instead, springs were retained only if at least 80 % of daily data was available within the reference period. The selected reference period represents a compromise between the need for sufficiently long time series for robust trend detection and the aim of retaining a large number of springs across the study area, particularly because data availability for Alpine karst springs drops markedly as the reference period increases. The hydrological year 2022 was selected as the final year as data availability in ALPAKAS declines for several countries in 2023. In total, 85 sites from six countries met these requirements and are listed in Table B1. These springs are widely distributed across the study region with annual mean discharges ranging between 0.4 and 22,700 L s⁻¹ and mean catchment elevations between 340 and 2580 m above mean sea level (a.m.s.l.). No systematic patterns of missing data were identified in the retained time series, such as complete

missing years affecting springs from a particular country. Although no station was considered to be substantially influenced by surface flow or water extraction, the analyzed data subset also includes stations located within a few hundred meters of the spring as well as springs that may have been subject to water extraction. These potential influences are indicated in ALPAKAS, together with extensive metadata and static attributes for all sites (Joger et al., 2026a).

ALPAKAS provides precipitation and temperature time series from a range of meteorological data products covering global, continental and national domains. The gridded data products were aggregated over both existing expert-based catchment delineations and circular catchment approximations based on an approach developed by Thinius et al. (2026). Thinius et al. (2026) showed that these catchment approximations provided a representation of meteorological forcing similar to that obtained from expert-based catchments and considerably better than that obtained using values extracted at the spring location, particularly for snow-influenced springs. In this study, precipitation and mean temperature variables from the daily observation-based gridded E-OBS dataset (Cornes et al., 2018) were used to ensure homogeneous representation of meteorological attributes across national boundaries. E-OBS is generated by interpolating quality-controlled station observations from the European Climate Assessment & Dataset (ECA&D) to a spatial resolution of 0.1° and is available in ALPAKAS as catchment-aggregated time series for the period 1950–2024. Expert-based catchment aggregates were used where available (65 karst springs), while circular catchment approximations were used for the remaining springs (20).

2.2 Hydrograph-based clustering and classification of karst springs

Springs meeting all requirements were grouped based on two complementary hydrograph-based approaches: (1) clustering of Pardé coefficients characterizing discharge seasonality, and (2) the KarstID classification framework characterizing karst-system hydrological functioning.

Pardé coefficients are widely used to characterize the seasonal distribution of discharge and have also been applied to karst springs (Schürch et al., 2016; Seelig et al., 2024). They are calculated by normalizing monthly mean discharge by the annual mean discharge computed over the same period (Pardé, 1933):

$$P_i = \frac{\bar{Q}_i}{\bar{Q}_a} \quad (1)$$

where P_i [-] is the Pardé coefficient for month i , $\bar{Q}_i$ [L s^{-1}] is the long-term mean discharge for month i , and $\bar{Q}_a$ [L s^{-1}] is the long-term mean annual discharge. Following Seelig et al. (2024), k-means clustering was applied to the Pardé coefficients by minimizing the within-cluster sum of squared Euclidean distances, and the number of clusters was selected using the elbow method, which identifies the point beyond which additional clusters yield only marginal reductions in within-cluster variance.

KarstID is an openly available R Shiny application allowing the classification of karst-system hydrological functioning based on indicators derived from recession-curve analysis (Cinkus et al., 2023). Within the KarstID workflow, users manually select recession events from the hydrograph and define the inflection point of Mangin’s recession model (Mangin, 1975) for each selected event. The indicators used for system classification are then automatically derived. The classification scheme was developed based on a multivariate analysis of recession-curve and statistical indicators for 10 karst systems with well-known hydrological functioning and tested on 78 karst systems worldwide (Cinkus et al., 2021). The final classification distinguishes six classes based on three indicators derived from Mangin’s recession model, which separates spring recession curves into an influenced (quickflow-dominated) and a non-influenced regime (baseflow-dominated): The parameter k_{max} characterizes the capacity of the dynamic storage, expressing the capacity of a system to temporarily store and dynamically release water during events. It represents the maximum value of the dynamic storage indicator k and is mainly linked to the non-influenced part of the recession curve. The parameter α_{mean} is closely related to k_{max} and describes the draining dynamic of the capacity function, representing the average rate at which stored water is released from the system during the non-influenced regime. IR characterizes the variability of the hydrological response and is associated with the influenced regime. Derived from the indicator i , which describes the degree to which a system filters and attenuates the precipitation signal, IR reflects the range of i values across the selected recession events.

All 85 time series were classified based on their full record length in ALPAKAS by selecting 2–10 recession events depending on their availability, closely following the procedure described by Cinkus et al. (2023). As IR is defined as the difference

between the maximum and minimum values of i , it strongly depends on the number of selected recession events (Cinkus et al., 2021) and was found to be highly sensitive to individual events in this study. In addition, Cinkus et al. (2021) clearly identified IR as the least explanatory parameter in their multivariate analysis. Therefore, this indicator was not considered for classification in the present study, resulting in three aggregated KarstID classes. Hereafter, the term KarstID classes refers to these aggregated classes: (1) C12: poor capacity of dynamic storage and fast draining dynamic of the capacitive function; (2) C34: poor capacity of dynamic storage and moderate draining dynamic of the capacitive function; and (3) C56: noticeable capacity of dynamic storage and slow draining dynamic of the capacitive function.

In a final step, following Seelig et al. (2024), the association between Pardé clusters and KarstID classes was assessed using a contingency table and Pearson's χ^2 test of independence, with significance evaluated using Monte Carlo-simulated p-values based on 10,000 replicates. Relative cell residuals were then calculated to identify over- and underrepresented combinations. Positive residuals indicate combinations occurring more frequently than expected under the assumption of independence, and these combinations were therefore identified as dominant spring groups further evaluated during trend analysis.

Our analysis of Pardé clusters and KarstID classes allows discharge regimes and karst-system response types to be evaluated both separately and in combination. A key advantage of the KarstID classification is that representative recession curves are selected individually using expert knowledge. This is particularly relevant for springs affected by delayed discharge from snow storage, for which autocorrelation-based clusters, as used by Seelig et al. (2024), may not reliably represent system properties because gradual meltwater release can lead to high annual periodicity in the autocorrelation function regardless of system storage behaviour.

2.3 Trend analysis

Monotonic trends in spring discharge and meteorological time series were assessed using the Mann-Kendall test (Mann, 1945; Kendall, 1975), with Sen's slope estimator (Sen, 1968) used to quantify trend magnitudes. Both are non-parametric methods commonly applied to hydrometeorological time series as they do not require normally distributed data. Because serial correlation can affect the significance of detected trends, we applied the modified Mann-Kendall test proposed by Hamed and Ramachandra Rao (1998), as implemented in the R package *modifiedmk* (Patakamuri and O'Brien, 2021). Trends were evaluated at significance levels of 0.05 and 0.10. The 0.10 threshold was included because a less strict significance level can improve the detection of trends in hydrometeorological records (Wang et al., 2020) and has been applied in comparable studies (Giese et al., 2025; Vremec et al., 2025). For discharge and precipitation variables, Sen's slopes were normalized by the respective long-term mean values and expressed as percentage change per year ($\% \text{ yr}^{-1}$). Trends were assessed for (1) annual mean discharge to identify long-term trends in overall discharge, and (2) seasonal mean discharges (winter: DJF; spring: MAM; summer: JJA; autumn: SON) as well as annual low-flow and high-flow indicators to identify patterns of seasonal flow redistribution. Low flows and high flows were defined separately for each hydrological year as the 10th percentile ($Q_{0.1}$) and the 90th percentile ($Q_{0.9}$) of daily discharge values, respectively. The analysis of seasonal flow redistribution was further supported by trend analyses of monthly mean discharge and Pardé coefficients. To assess potential hydroclimatic controls on observed discharge trends, monthly mean precipitation and temperature trends were assessed. Annual, seasonal, and monthly means were considered only for trend analysis when at least 80 % of daily values were available within the respective aggregation period. Finally, trends in timing of low flow and high flow were computed to further assess seasonal flow redistribution. Timing was analyzed using circular statistics, following Blöschl et al. (2017) and adapting the code provided by Klotz et al. (2026). In contrast to their focus on annual maximum flow timing, we derived low-flow and high-flow timing from all days within each hydrological year on which discharge was below $Q_{0.1}$ or above $Q_{0.9}$, respectively. These days were converted to angular values, averaged using their mean sine and cosine components, and transformed back to day of the hydrological year. Following Klotz et al. (2026), timing trends were quantified using an adjusted Sen's slope, defined as the median of all pairwise slopes between annual timing values. Differences exceeding half the mean hydrological-year length were adjusted by one year length to account for the circular year boundary. Positive and negative slopes indicate shifts toward later and earlier timing, respectively, expressed in days per year. All trends were analyzed by Pardé cluster, KarstID class, and dominant spring group.

Due to the limited availability of discharge time series with sufficient data completeness, a relatively short reference period of 20 years was selected (2003–2022). Because trend estimates from relatively short time series can be particularly sensitive to anomalous conditions occurring at the beginning or end of the analysis period (Hannaford et al., 2013), we tested the sensitivity

of the results to the boundary years. Therefore, the trend analysis was repeated after excluding the first and last hydrological year of the reference period, respectively, and the resulting trend estimates were compared with those obtained for the full reference period (Appendix D).

3 Results

3.1 Characteristics of identified karst spring groups

The clustering based on the Pardé coefficients identifies four distinct clusters, presented in Fig. 1 (a). The clusters are further described using static ALPAKAS attributes, including structural tectonic unit, climate zone, mean catchment elevation, and mean discharge.

- PC1 ($n = 29$) represents a winter-pluvial discharge regime with strong seasonality. Hydrographs in this cluster are characterized by high winter discharge, with an average monthly maximum in December ($P_{max} = 1.6$), followed by a pronounced decline toward a minimum in August ($P_{min} = 0.4$). Springs assigned to this cluster are mainly located in the Jura Mountains, Dinarides, and Provence Platform and are generally situated at lower elevations in a warm-temperate climate. The median mean catchment elevation is 710 m, and the median mean discharge is 2310 L s^{-1} .
- PC2 ($n = 31$) represents hydrologically buffered systems with weak seasonality. Most hydrographs show a weak pluvio-nival discharge regime, with elevated discharge in spring, indicating a moderate snowmelt contribution. The cluster maximum occurs in April ($P_{max} = 1.2$), while the minimum occurs in December ($P_{min} = 0.9$). Springs assigned to this cluster are broadly distributed across the study region and are mostly located in areas characterized by a boreal climate. They cover a range of mean catchment elevations, although very low and very high-elevation sites are absent. The median mean catchment elevation is 990 m, and the median mean discharge is 140 L s^{-1} .
- PC3 ($n = 13$) represents a nivo-pluvial discharge regime characterized by low winter discharge and a pronounced peak in May ($P_{max} = 2.2$), indicating dominant seasonal snowmelt control. After a rapid decline, the Pardé curve remains close to average in late summer and early autumn before discharge decreases again in autumn and winter. The minimum occurs in December ($P_{min} = 0.5$). Springs assigned to this cluster are mainly located in the eastern part of the Northern Calcareous Alps within the Eastern Alps, in areas characterized by a boreal climate, and are associated with mid- to high-elevation catchments. The median mean catchment elevation is 1470 m, and the median mean discharge is 480 L s^{-1} .
- PC4 ($n = 12$) represents a nival discharge regime, with very low winter discharge, a delayed onset of snowmelt followed by a pronounced peak in June ($P_{max} = 2.0$), and a long, gradual recession during the second half of the year. The minimum occurs in February ($P_{min} = 0.4$). Springs assigned to this cluster are strongly snow-dominated, located in the Eastern Alps and Helveticum, in areas characterized by a boreal climate. They are associated with high mean catchment elevations, with a median of 1900 m, and a median mean discharge of 270 L s^{-1} .

The KarstID classification yields a relatively even distribution across classes, with 35 springs assigned to C12, 27 to C34, and 23 to C56. Fig. 1 (b) reveals some spatial patterns, particularly a tendency toward faster-responding springs in the Jura Mountains, Dinarides, and parts of the eastern Northern Calcareous Alps. Overall, however, KarstID classes are distributed across the study region, and show no clear elevation-dependent pattern. Median mean discharges are 1070 L s^{-1} for C12, 260 L s^{-1} for C34, and 140 L s^{-1} for C56, indicating that faster-responding springs tend to have higher discharges.

The comparison of Pardé clusters (Fig. 1 (c)) shows a close relationship between cluster membership and mean catchment elevation. PC2 exhibits the broadest elevation range and partly overlaps with both PC1 and PC3, consistent with its description as a group of hydrologically buffered systems rather than a distinct discharge regime. Almost all springs assigned to C56 fall within PC2, indicating an association between high-storage, slowly draining systems and weakly seasonal discharge regimes. Median mean discharge is highest in PC1, which includes several large springs and major resurgences, and lowest in PC2. Within the individual Pardé clusters, C12 springs generally show the highest median mean discharges.

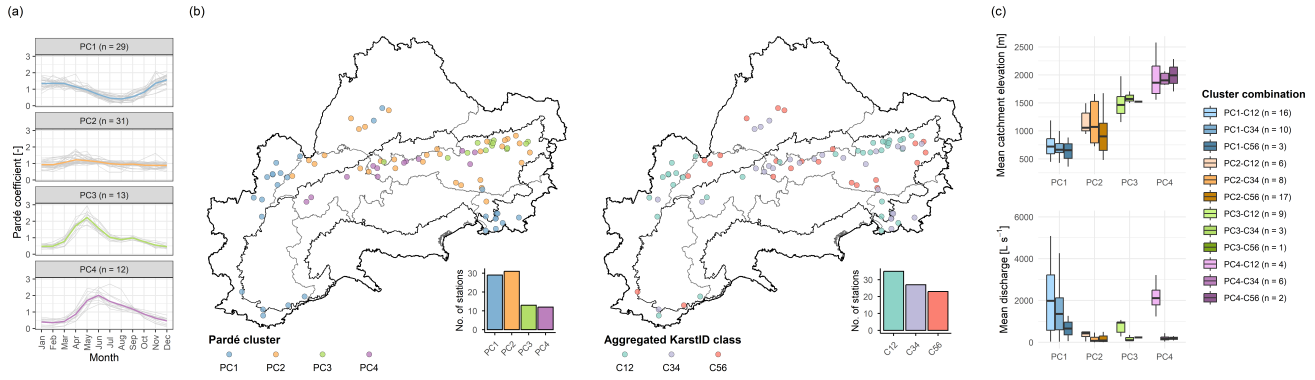


Figure 1: (a) Monthly Pardé-coefficient curves with cluster centers represented by colored lines and the respective cluster members by grey lines. (b) Spatial distributions of Pardé clusters and KarstID classes across the study region. (c) Boxplots of mean catchment elevation and mean discharge by Pardé cluster and KarstID class. Administrative borders: © 2018–2025 GADM. Alpine Convention perimeter: Eurac Research and Permanent Secretariat of the Alpine Convention (2025).

The Pardé clusters and KarstID classes result in twelve possible cluster combinations. The χ^2 test indicates a highly significant association between the two groupings ($p \leq 0.0007$). Based on the contingency table shown in Fig. A1, five combinations exhibit positive standard residuals and are therefore considered overrepresented relative to an independent distribution of the two groupings. Together, these five dominant spring groups account for more than two thirds of all springs and were retained for supplementary analysis. While the dominant spring groups integrate information on both discharge seasonality and karst-system characteristics, the relatively small number of springs within some groups limits the robustness of group-wise comparisons. The dominant spring groups, their spatial distribution across the study region, and the corresponding results of the trend analyses are therefore briefly described in Appendix A. The Pardé cluster, KarstID class, and dominant spring group assigned to each analyzed spring are listed in Table B1, together with the normalized Sen's slopes for annual and seasonal mean discharge, as well as for low and high flows.

3.2 Trends in annual mean discharge and low-flow and high-flow indicators

Fig. 2 (a) shows a reduction in annual mean discharge at most sites, with negative trends occurring mainly in the European Foreland, the Jura Mountains, and the eastern part of the Northern Calcareous Alps. Across the study region, 17 significant negative and eight significant positive trends are detected ($p < 0.10$). Positive trends are predominantly observed in the southern part of the study region and in high-elevation catchments of the Central Alps, represented by PC4. Overall, however, only a weak association with elevation is observed. PC2 and PC3 show clearly negative median trends, representing mainly mid-elevation catchments. With respect to KarstID classes, no clear differences are observed.

Low-flow trends (Fig. 2 (b)) show a clear spatial pattern across the study region. Negative trends mostly occur in the peri-Alpine region, defined here as the part of the EUSALP area outside the Alpine Convention perimeter, whereas positive trends are predominantly found in the core Alpine region, defined as the area within the Alpine Convention perimeter. In total, 16 springs show significant negative trends and 14 springs show significant positive trends. A clear positive association with catchment elevation is observed ($\rho = 0.55$, $p < 0.001$), which is also reflected in the median trends of the Pardé clusters. While PC1 shows mainly negative low-flow trends, mixed trends are found for PC2, and clearly positive trends are observed for PC3 and PC4. High-flow trends (Fig. 2 (c)) broadly follow the spatial distribution of annual mean discharge trends. Negative trends occur predominantly in the European Foreland, the Jura Mountains, and the eastern part of the Northern Calcareous Alps, whereas positive trends occur mainly in the southern part of the study region. Overall, eleven significant positive and six significant negative trends are observed. PC1 shows a slightly positive median trend, while PC2 and PC3 show negative median trends. For both low-flow and high-flow trends, no distinct differences are observed among KarstID classes, and variability within classes is relatively high. However, C56 tends to show less extreme trends.

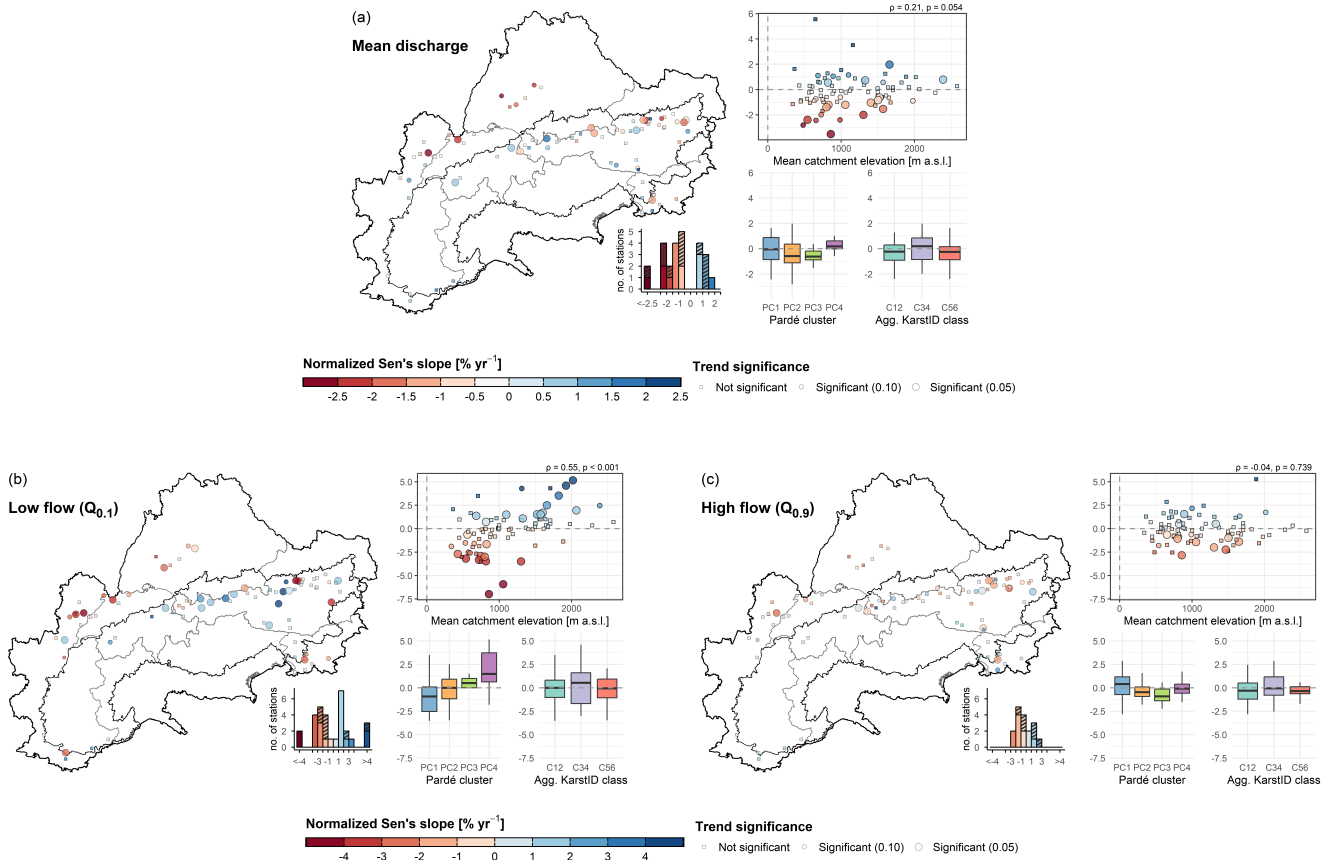


Figure 2: Summary of trend analysis results for (a) mean discharge, (b) low flows, and (c) high flows, computed over hydrological years. Each panel shows the spatial distribution of trend magnitudes across individual springs, with trend significance indicated at the $p < 0.05$ and $p < 0.10$ levels. The accompanying histogram shows the distribution of significant trends, with trends significant only at the 0.1 level shown as hatched bars. A scatter plot shows the association between trend magnitude and mean catchment elevation, including Spearman's ρ and the corresponding p -value. Boxplots show trends grouped by Pardé cluster and aggregated KarstID class. Administrative borders: © 2018–2025 GADM. Alpine Convention perimeter: Eurac Research and Permanent Secretariat of the Alpine Convention (2025).

275 3.3 Trends in seasonal discharge

Fig. 3 (a) shows predominantly positive winter discharge trends in the core Alpine region and the Jura Mountains. Across the study region, 31 springs show significant increases and only one spring shows a significant decrease. Winter discharge trends show a clear association with elevation, with higher mean catchment elevations associated with more positive trends ($\rho = 0.41, p < 0.001$). This pattern is also reflected in the Pardé clusters, with PC3 and PC4 showing the highest median trends.

280 Discharge trends in spring (Fig. 3 (b)) are mostly negative in the peri-Alpine region, whereas the core Alpine region shows predominantly positive trends, except for the eastern part of the Northern Calcareous Alps. Across the entire study region, five significant increasing and nine significant decreasing trends are detected. As in winter, discharge trends in spring show a clear positive association with elevation ($\rho = 0.41, p < 0.001$), which is also reflected in the Pardé clusters. A positive median trend is observed only for PC4.

285 Summer discharge trends (Fig. 3 (c)) vary across the study region but are predominantly negative, with two significant positive and ten significant negative trends. No clear association with elevation is observed. The strongest median trend occurs in PC3 and is negative, mainly reflecting decreasing summer discharge trends in the eastern part of the Northern Calcareous Alps.

Discharge trends in autumn (Fig. 3 (d)) are mostly negative in the European Foreland and the Jura Mountains, but predominantly positive in the Dinarides and near the Provence Platform. Across the study region, three significant positive and seven significant

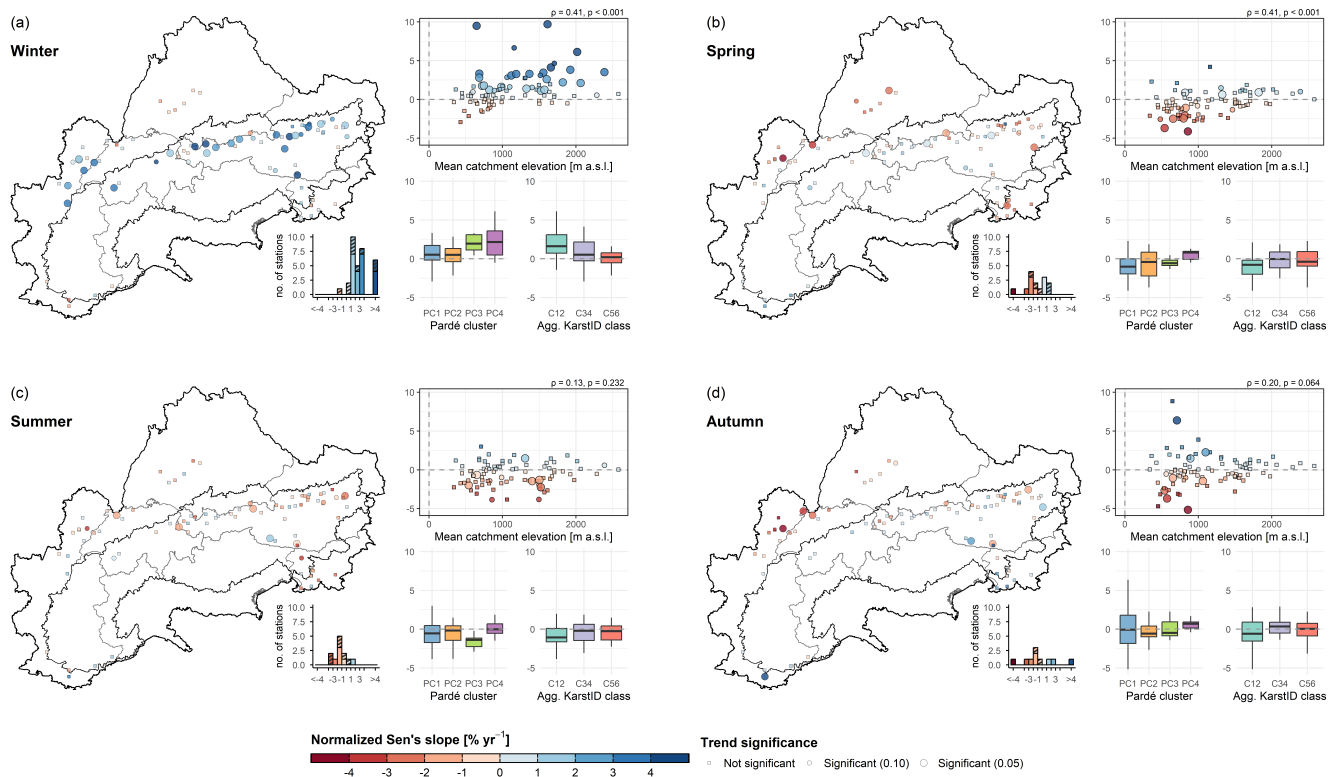


Figure 3: Summary of trend analysis results for seasonal discharge in (a) winter, (b) spring, (c) summer, and (d) autumn. Each panel shows the spatial distribution of trend magnitudes across individual springs, with trend significance indicated at the $p < 0.05$ and $p < 0.10$ levels. The accompanying histogram shows the distribution of significant trends, with trends significant only at the 0.1 level shown as hatched bars. A scatter plot shows the association between trend magnitude and mean catchment elevation, including Spearman's ρ and the corresponding p -value. Boxplots show trends grouped by Pardé cluster and aggregated KarstID class. Administrative borders: © 2018–2025 GADM. Alpine Convention perimeter: Eurac Research and Permanent Secretariat of the Alpine Convention (2025).

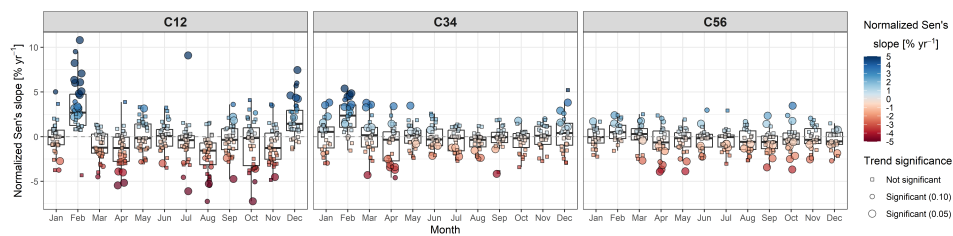


Figure 4: Boxplots with individual trends in monthly discharge per aggregated KarstID class and trend significance indicated at the $p < 0.05$ and $p < 0.10$ levels.

290 negative trends occur. Trend directions and magnitudes vary strongly within PC1, reflecting the opposing trends among different structural tectonic units in the peri-Alpine region. Only PC4 shows a positive median trend.

Grouping by KarstID classes reveals a clear tendency for faster-responding springs to show larger winter trend magnitudes, reflected in both median and extreme trends. Differences are less distinct for the other seasons. At the monthly scale, however, differences among KarstID classes become much more pronounced (Fig. 4), with C12 generally showing the largest and C56 the smallest trend magnitudes and variability.

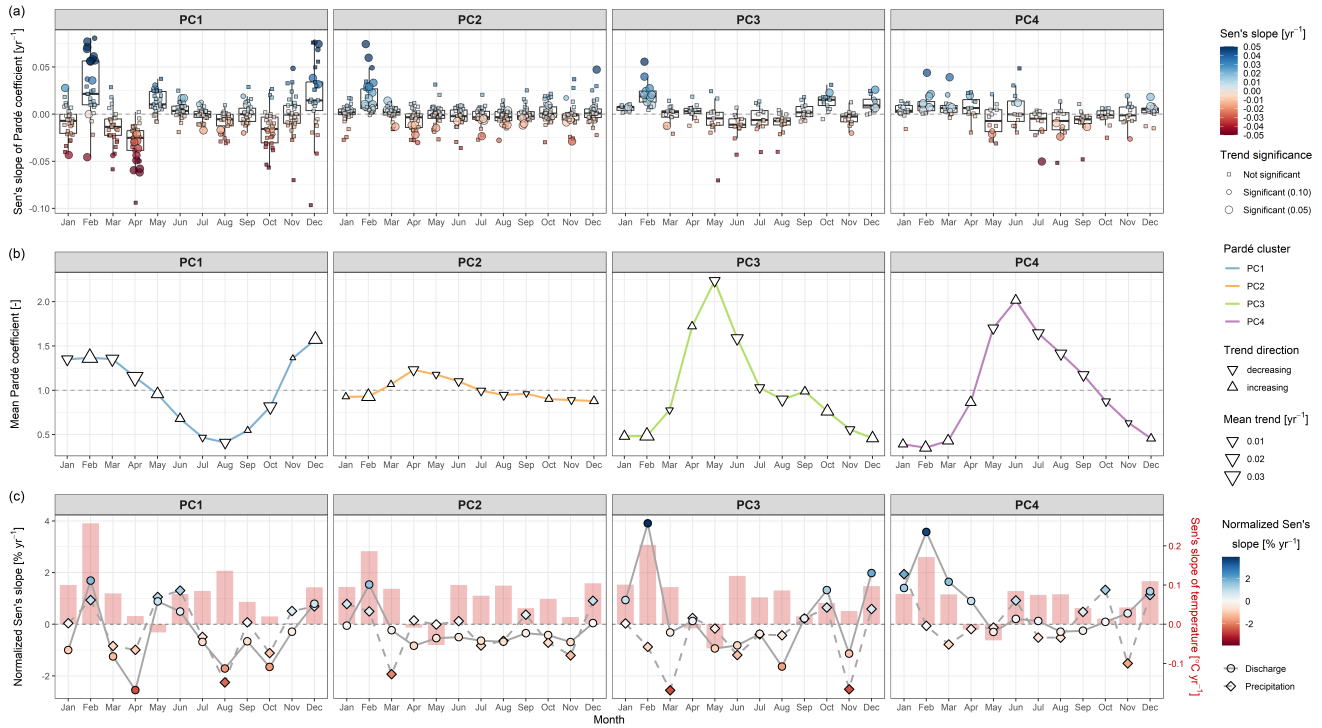


Figure 5: (a) Boxplots with individual trends in monthly Pardé coefficients per Pardé cluster and trend significance indicated at the $p < 0.05$ and $p < 0.10$ levels, (b) mean monthly Pardé coefficients combined with the mean trend of monthly Pardé coefficients for each Pardé cluster, and (c) normalized mean monthly precipitation, temperature, and discharge trends averaged across all springs within each Pardé cluster.

3.4 Trends in discharge seasonality, hydrometeorological variables, and flow timing

Trends in discharge seasonality and hydrometeorological variables were evaluated primarily by discharge regime, as represented by the Pardé clusters, which reflect differences in hydroclimatic controls on seasonal discharge patterns. Fig. 5 (a & b) shows distinct patterns in the trends of monthly Pardé coefficients among the Pardé clusters. Across all Pardé clusters, the highest median trends occur in February, coinciding with the strongest positive temperature trends in this month (Fig. 5 (c)). Overall, mean monthly temperature trends show a similar seasonal pattern across Pardé clusters, with increasing temperatures in most months and negative trends in April and May for most clusters. However, annual mean temperature trends decrease progressively from PC1 through PC2 and PC3 to PC4.

For PC1, Pardé trends vary strongly among months. Monthly trends indicate increasing relative discharge contributions in December, February, May, and June. Pronounced negative trends are observed in March, April, and October, with a large number of springs with significant negative trends in April. PC1 shows the strongest overall change in seasonality, with an increase in seasonal contrast. Moreover, PC1 shows a strong association between precipitation and discharge trends throughout the annual cycle.

For PC2, trends indicate increasing relative discharge contributions in winter and early spring, particularly in February, while most months from April to September show decreasing tendencies. PC2 exhibits the smallest change in seasonality, consistent with the comparatively low overall seasonality of springs assigned to this cluster. However, discharge trends still broadly follow the annual cycle of precipitation trends for most of the year, albeit in a clearly buffered form. Exceptions occur in February, when discharge trends show a pronounced positive peak, and in March, when precipitation trends are considerably more negative than discharge trends. From April to June, negative discharge trends coincide with non-negative precipitation trends.

For PC3, mean monthly trends indicate increasing relative discharge contributions in October and during the winter months, while trends from May to August are predominantly negative. PC3 shows a clear change in seasonality, with an overall decrease in seasonal contrast. For PC3, discharge trends broadly follow the precipitation trends from April to January. In February,

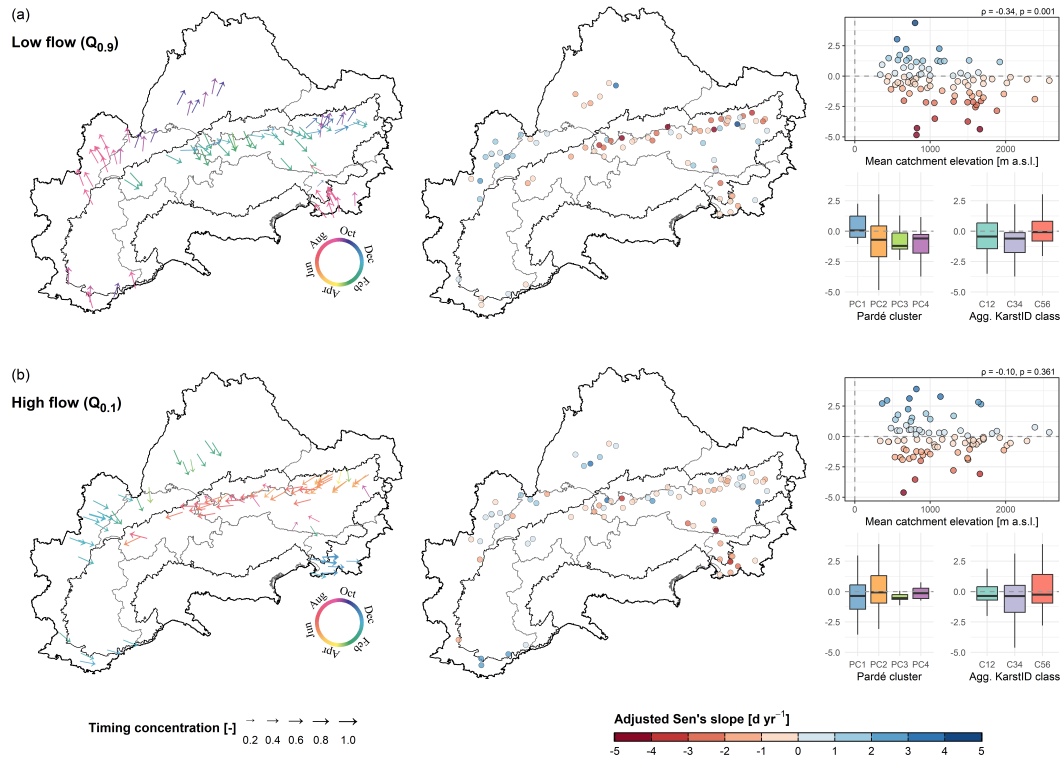


Figure 6: Timing of (a) low flows and (b) high flows, derived from all days within each hydrological year on which discharge was below $Q_{0.1}$ or above $Q_{0.9}$, respectively. Each panel shows the spatial distribution of average flow timing across the study region, following Blöschl et al. (2017) and using an adapted version of the code provided by Klotz et al. (2026). Each arrow represents one karst spring, with color and direction indicating average timing and arrow size indicating the temporal concentration of timing across years. Values close to 0 indicate highly variable timing among years, whereas values close to 1 indicate that low-flow or high-flow timing is concentrated around a similar period each year. Each panel additionally includes the spatial distribution of trends in average flow timing across individual springs and a scatter plot showing the association between trend magnitude and mean catchment elevation, including Spearman's ρ and the corresponding p -value. Boxplots show timing trends grouped by Pardé cluster and aggregated KarstID class. Administrative borders: © 2018–2025 GADM. Alpine Convention perimeter: Eurac Research and Permanent Secretariat of the Alpine Convention (2025).

however, discharge trends show a pronounced positive peak despite negative precipitation trends. In March, precipitation trends are clearly more negative than discharge trends.

320 For PC4, relative discharge contributions increase from December to April, whereas most months from May to September show decreasing trends. Trends in the peak flow month of June are variable. Overall, this redistribution indicates a reduction in seasonality. Discharge and precipitation trends show relatively low correspondence, particularly from November to April. In November, discharge shows a positive trend despite clearly negative precipitation trends. From February to April, discharge shows clear positive trends despite non-positive precipitation trends.

325 Average low-flow and high-flow timing shows pronounced spatial patterns across the study region, with clear contrasts between the core Alpine and peri-Alpine regions and generally high timing concentration across hydrological years (Fig. 6). Overall, timing trends are less distinct than the average timing patterns, with no clear differences among aggregated KarstID classes. Across both low- and high-flow timing, PC2 shows highly variable timing trends, consistent with greater timing flexibility under weak seasonality.

330 Low flows mainly occur in winter in the core Alpine region (Fig. 6(a)). An exception is the eastern part of the Northern Calcareous Alps, where low flows predominantly occur in autumn. In the peri-Alpine region, low flows mostly occur in late summer to early autumn, whereas springs in the European Foreland tend to reach low-flow conditions in mid-autumn. Low-flow timing trends indicate a moderate negative association with elevation ($\rho = -0.34$, $p = 0.001$) and a general shift toward earlier

occurrence for PC2, PC3, and PC4. For PC1, most low-flow timing trends are negative, except in the Jura Mountains, where low flows tend to shift later.

High flows occur in late spring to early summer for most springs in the core Alpine region (Fig. 6(b)). In the peri-Alpine region, high flows occur in winter, with early-winter timing in the Dinarides and late-winter timing in the European Foreland. High-flow timing shifts are less pronounced than those of low flows, with negative trends occurring mainly in PC3 and the Dinarides and positive trends mainly among the remaining PC1 springs.

4 Discussion

4.1 Spatial and regime-specific patterns in discharge trends

Trends in annual discharge metrics are spatially heterogeneous across the wider Alpine region, with distinct regional patterns in annual mean discharge, low flows, and high flows. These spatial patterns are more pronounced than those reported by Giese et al. (2025) and Vremec et al. (2025), likely reflecting the larger number of springs and broader elevation gradients covered by our study. Among significant annual mean discharge trends, negative trends dominate, in line with previous analyses of observed discharge trends at karst springs in Central Europe and the Mediterranean (Jelen et al., 2020; Fiorillo et al., 2021; Fan et al., 2023; Vremec et al., 2025; Toran et al., 2026), as well as with projected decreases in discharge for individual karst systems (Chen et al., 2018; Casati et al., 2024). Significant negative trends are concentrated in the European Foreland, the Jura Mountains, and the eastern part of the Northern Calcareous Alps, whereas positive trends occur mainly in the southern part of the study region and in high-elevation catchments of the core Alpine region. High-flow trends broadly follow the spatial pattern of annual mean discharge trends, although fewer trends are significant. In contrast, low-flow trends show a pronounced association with elevation, shifting from predominantly negative trends in the peri-Alpine region to increasingly positive trends in the core Alpine region. This pattern suggests that low flows are particularly sensitive to elevation-dependent changes in the seasonal availability of delayed recharge, as discussed in more detail in Sect. 4.2.

Seasonally, widespread increases in winter discharge in the core Alpine region and the Jura Mountains, together with mainly negative spring and summer discharge trends outside high-elevation catchments, indicate a redistribution of discharge toward winter. The increasingly positive winter and spring discharge trends with increasing mean catchment elevation are consistent with pronounced elevation-dependent changes in snow accumulation and melt dynamics under climate warming (Beniston et al., 2018; Matiu et al., 2021). Trends in monthly Pardé coefficients show that the magnitude and seasonal expression of this redistribution differ among discharge regimes. This translates into increasing seasonality for PC1 and decreasing seasonality for PC2, PC3, and PC4. For PC1, increasing seasonal contrast tends to strengthen the already pronounced winter-pluvial regime. Among the snow-influenced regimes, the strongest reduction in seasonality occurs in PC3, where the pronounced spring-dominated nivo-pluvial regime weakens due to higher relative contributions in winter and decreasing contributions from May to August, when Pardé coefficients indicate the main seasonal discharge contribution. PC4 shows a similar but more prolonged redistribution pattern, with increasing relative contributions from winter to mid-spring and decreasing contributions throughout much of the summer, although trends in June Pardé coefficients vary among sites, as further discussed in Sect. 4.2. PC2 broadly follows the pattern for PC3 but exhibits the smallest overall change, consistent with its comparatively weak seasonal regime.

Changes in flow timing provide complementary evidence for contrasting redistribution patterns between the core Alpine region and the peri-Alpine region. The overall tendency toward earlier low-flow occurrence for PC2, PC3, and PC4 is likely linked to strongly increasing February discharge, which reduces the occurrence of low-flow days in late winter and thereby shifts mean low-flow timing earlier. Low-flow timing may therefore provide an indirect indicator of earlier snowmelt in these snow-influenced regimes. Trends in high-flow timing are less pronounced and show no consistent shift toward earlier occurrence, although earlier snowmelt might be expected to advance both the snowmelt peak and the depletion of seasonal snow storage, as discussed by Vremec et al. (2025).

Taken together, the analyses indicate that the hydrological response to recent climatic change is strongly structured by discharge regime, which is closely associated with elevation. The observed association with elevation and widespread increase in winter discharge are consistent with previous streamflow studies from Alpine catchments, which likewise found seasonal trends to be

more pronounced than annual trends (Stahl et al., 2010; Bard et al., 2015; Blöschl et al., 2018; Kormann et al., 2015). The observed redistribution is also qualitatively consistent with projected changes in Alpine streamflow, which generally indicate increasing winter runoff, decreasing summer runoff, and elevation-dependent shifts in spring runoff and flow timing (Hanus et al., 2021; Muelchi et al., 2021a,a; Brunner et al., 2019). In agreement with the present study, Vremec et al. (2025) identified seasonal redistribution mainly characterized by generally increasing winter discharge and low flows across Austrian springs, using the annual 7-day minimum flow as low-flow indicator. They also identified declining spring and summer discharge for a spring group in the eastern part of the Northern Calcareous Alps, whose sites are predominantly karstic and largely correspond to PC3 in the present study. For this spring group, they reported decreasing seasonality associated with increasing low flows and an earlier timing of both low flows and high flows, with high flows represented by the annual maximum flow. Our results show that this pattern of decreasing seasonality and earlier low-flow timing extends beyond the Austrian Alps for karst springs and reveal contrasting responses between the core Alpine region and the peri-Alpine region. In the core Alpine region, reduced seasonal discharge contrasts may lead to more sustained winter flows and potentially alleviate water-availability constraints, including for hydropower generation (Wagner et al., 2017), whereas reduced summer discharge may increase water-availability constraints in the peri-Alpine region.

4.2 Hydroclimatic controls across discharge regimes

The combined analysis of monthly Pardé trends and precipitation–discharge trend patterns (Fig. 5) indicates that seasonal flow redistribution differs markedly among the identified discharge regimes. Seasonal flow redistribution can generally result from two main hydroclimatic controls: (i) changes in rainfall seasonality and amount, together with changes in evapotranspiration, can directly alter the timing and magnitude of effective recharge, and (ii) warming-induced changes in snow and ice storage can modify delayed recharge by shifting rain–snow partitioning and advancing meltwater release. The analysis does not aim to quantitatively partition recharge into direct and delayed components, which would require additional data or process-based modelling approaches. Rather, the comparison of precipitation, temperature, and discharge trends is used to identify associations that are consistent with dominant controls on seasonal flow redistribution across discharge regimes.

The winter-pluvial regime represented by PC1 shows the closest correspondence between mean precipitation and discharge trends, despite encompassing springs from widely separated locations in different structural tectonic units. This correspondence suggests that seasonal flow redistribution in PC1 is primarily controlled by changes in precipitation seasonality and that these systems respond relatively directly to seasonal precipitation changes. Similar patterns were observed by Giese et al. (2025) for the Jura Mountains, where increasing winter discharge trends and decreasing autumn discharge trends were associated with corresponding shifts in seasonal precipitation. Likewise, Jelen et al. (2020) attributed long-term decreases in annual mean discharge and low flows at Slovenian karst springs primarily to declining precipitation. The comparatively direct response of PC1 is consistent with the dominant KarstID classes in this regime, for which only three out of 29 springs are classified as high-storage, slowly draining systems. Moreover, no strong contribution of earlier meltwater release is evident, consistent with the comparatively low influence of seasonal snow storage expected for most low-elevation catchments in the peri-Alpine region. The close correspondence between precipitation and discharge trends is remarkable, suggesting both that E-OBS precipitation data capture the broad seasonal precipitation changes reasonably well for stations in the peri-Alpine region and that discharge for springs assigned to PC1 responds to precipitation changes within a comparable relative range. While this correspondence suggests a dominant role of precipitation changes, evapotranspiration was not evaluated separately and may also have contributed to the observed discharge trends, particularly given its expected importance in lower-elevation catchments (Dumont et al., 2025; Muelchi et al., 2021b) and the comparatively strong temperature trends in PC1.

PC2 shows a clearly buffered discharge response, which is consistent with the KarstID classification, as only six of the 31 springs are characterized as low-storage, fast-draining systems. Discharge trends broadly follow precipitation trends, but clear deviations in late winter and spring indicate an influence of delayed recharge processes. The pronounced positive discharge trend in February is consistent with an increasing contribution from earlier snowmelt (Bard et al., 2015; Kormann et al., 2015; Matiu et al., 2021), as also suggested by the strongly positive temperature trend for February. This signal appears to persist into March, when strongly negative precipitation trends are not accompanied by similarly negative discharge trends. The mismatch between discharge and precipitation trends from April to June may indicate a reduced contribution of delayed snowmelt

425 recharge following earlier meltwater release during winter or early spring, as also suggested by the earlier timing of low-flow trends.

PC3 shows a similar snow-related redistribution but a stronger seasonal response. Although precipitation and discharge trends correspond relatively closely over most of the year, seasonal flow redistribution cannot be explained by precipitation trends alone. As for PC2, the pronounced increase in February discharge and the much weaker discharge decline relative to precipitation in March are consistent with an earlier contribution of snowmelt recharge. This interpretation is consistent with Vremec et al. (2025), who associated increasing winter discharge in the Northern Calcareous Alps with warming-induced changes in snow accumulation and melt dynamics.

A similar pattern is observed for PC4, although the clearly positive discharge trends from February to April suggest a more prolonged early-season snowmelt contribution. The absence of a corresponding discharge decline in November further suggests that same-month precipitation exerts comparatively limited control on discharge during this period, likely because precipitation is temporarily stored as snow. The comparatively more buffered response relative to PC3 is consistent with the higher catchment elevations for PC4, where snow and ice storage can influence discharge over large parts of the year (Beniston et al., 2018). The variable June Pardé trends may reflect enhanced snow accumulation associated with increased precipitation at high elevations or glacier melt contributions from long-term ice storage in some catchments, as reported for high-elevation catchments in previous studies on Alpine streamflow (Bard et al., 2015; Kormann et al., 2015). PC4 contains three springs that are clearly influenced by glaciers (AT-0002: Waldbachursprung; CH-0003: Siebenbrünnen; CH-0021: Glarey). However, only Waldbachursprung shows a distinct positive trend, with a Sen's slope of 0.030 in June, suggesting that glacier influence alone does not explain the heterogeneous response. Vremec et al. (2025) similarly reported only weak spring, summer, and autumn discharge trends for a high-alpine spring group that is predominantly associated with PC4 in the present study, which they interpreted as indicating a comparatively low sensitivity to warming-related seasonal shifts. Our analysis at the monthly scale suggests that the differences in precipitation forcing contribute substantially to the contrasting responses of PC3 and PC4, with PC3 showing clearly more pronounced negative precipitation trends during these seasons than PC4.

Overall, the analysis indicates contrasting hydroclimatic controls across the discharge regimes. Seasonal flow redistribution in PC1 appears to be primarily associated with changes in precipitation seasonality, whereas changing snow storage patterns appear to contribute increasingly to discharge redistribution for PC2, PC3, and PC4, with their relative importance and seasonal expression closely related to mean catchment elevation. This association with elevation is consistent with previous Alpine studies showing that warming-induced changes in snow accumulation and melt dynamics become increasingly important at higher elevations, whereas changes in precipitation and evapotranspiration gain relative importance toward lower elevations (Dumont et al., 2025; Muelchi et al., 2021b; Matiu et al., 2021).

455 **4.3 Discharge trends in relation to karst-system response types**

Overall, the observed discharge trend patterns are more clearly structured by Pardé clusters than by KarstID classes. This is hydrologically plausible, as the Pardé clusters represent different discharge regimes that are closely associated with elevation and corresponding hydroclimatic controls on recharge (Vremec et al., 2025; Bard et al., 2015; Kormann et al., 2015). Accordingly, the dominant spring groups primarily reflect differences in discharge regime, while the KarstID classes provide additional insight into how karst-system properties modulate the transmission of hydroclimatic signals to spring discharge. This finding is further supported by the general similarity between observed karst spring trends and reported streamflow trends, suggesting that karst recharge is primarily influenced by the same hydroclimatic changes that govern surface runoff. The weaker separation among KarstID classes is consistent with the hydroclimatic-control analysis (Sect. 4.2), which shows that even the comparatively buffered karst systems represented by PC2 exhibit considerable correspondence between monthly precipitation and discharge trends throughout much of the year. Consequently, even karst springs with substantial storage and buffering can be sensitive to changes in hydroclimatic forcing on relatively short timescales, supporting the broader use of karst springs as robust regional climate indicators (Fiorillo et al., 2021; Giese et al., 2025).

Karst-system properties nevertheless appear to modulate spring responsiveness. Differences among KarstID classes are most pronounced in winter, when seasonal flow redistribution is strongest, with faster-responding springs tending to exhibit both larger trend magnitudes and greater variability. This gradient in sensitivity to hydroclimatic change, decreasing from the

faster-responding C12 systems through C34 to the slower-responding C56 systems, becomes even clearer at the monthly scale, indicating that seasonal aggregation can mask differences in spring responsiveness. This pattern is consistent with the stronger transmission of climatic forcing expected in highly karstified systems with fast groundwater dynamics (Chen et al., 2018; Hartmann et al., 2017).

These findings partly contrast with Giese et al. (2025), who identified no clear relationship between spring discharge trends and karst-system properties represented by baseflow and memory indices. Similarly, Toran et al. (2026) found no systematic relationship between discharge variability and long-term discharge trends across 31 springs in Europe and the United States over a common reference period, a finding they interpreted as suggesting that groundwater storage may buffer hydroclimatic changes even in rapidly responding karst systems. These apparent differences may partly reflect the masking effect of temporal aggregation discussed previously, as both studies assessed relationships between long-term discharge trends and karst-system characteristics, whereas our study reveals much clearer differences among karst-system response types at the monthly scale. Nevertheless, our findings and those of both studies suggest that karst systems with comparatively large storage capacities can still exhibit clear responses to changing hydroclimatic forcing. Furthermore, Vremec et al. (2025) observed contrasting discharge trends among spring groups with different hydrogeological and climatic characteristics but could not directly attribute these differences to specific system properties, while Casati et al. (2024) likewise found climatic forcing to exert a stronger influence on spring discharge than hydrogeological setting.

4.4 Uncertainties and limitations

The hydrometeorological time series obtained from the ALPAKAS dataset are subject to several uncertainties and limitations, which are discussed in detail by Joger et al. (2026a). These include uncertainties related to sensor calibration and rating curves, changes in measurement infrastructure and site conditions, heterogeneous temporal resolution, and varying data quality and prior preprocessing practices among data providers. ALPAKAS partly addresses these uncertainties by applying uniform preprocessing and quality control, complemented by quality flags and metadata. However, uncertainties inherent in the original observations may remain despite this harmonization. None of the analyzed stations showed substantial influence from surface water contributions or water extraction, although influences may still occur at some springs, as indicated in the metadata.

Additional uncertainties are associated with the catchment-aggregated E-OBS data adopted from ALPAKAS. E-OBS is based on interpolation of station observations and is therefore affected by spatially and temporally varying station coverage and interpolation uncertainty, with greater uncertainties in data-sparse regions (Cornes et al., 2018). Its relatively coarse nominal grid resolution of $0.1^\circ \times 0.1^\circ$ may further limit the representation of small-scale and elevation-dependent variability in meteorological forcing. In the Alps, these limitations are particularly relevant for high-elevation catchments due to sparse station coverage, complex topography, and increased uncertainty in underlying gauge measurements (Isotta et al., 2014). Together, these factors can lead to spatial smoothing and an underrepresentation of local variability and high precipitation amounts (Bandhauer et al., 2022).

Catchment delineation is particularly challenging for karst springs, as groundwater divides do not necessarily coincide with topographic watershed boundaries (Ford and Williams, 2007a). Uncertainties and limitations associated with the catchment approximations are discussed in detail by Thinius et al. (2026). Although catchment approximations can differ considerably from expert-based catchments in terms of size and geometry, Thinius et al. (2026) found that they provide reasonable estimates of catchment-scale precipitation and temperature, performing clearly better than values extracted at spring locations, particularly for snow-influenced catchments. Additionally, differences in the derived meteorological variables are expected to be relatively small given the coarse spatial resolution of the meteorological forcing data.

Uncertainties also arise from the spring classification and time series analysis. Although aggregating KarstID classes likely reduces the influence of uncertainty in individual class assignments, the underlying classification remains sensitive to the manual selection of recession events, as well as the number and representativeness of the available events (Cinkus et al., 2021). The relatively short 20-year reference period may limit the detection of hydrometeorological trends but represents a compromise between sufficient record length for robust trend detection and broad spatial coverage across the study area. The sensitivity analysis in Appendix D showed that excluding either boundary year affected the trend estimates, but overall trend patterns remained largely robust, suggesting that main the conclusions are not driven by individual boundary years.

Finally, groundwater recharge was not assessed in this study because robust catchment-scale estimates were unavailable. Instead, precipitation and temperature trends were used to evaluate associations between hydroclimatic forcing and spring discharge. This represents an important limitation for assessing how karst-system properties modulate the transmission of recharge signals to spring discharge. A more direct assessment would require regionally consistent catchment-scale recharge estimates, which could be obtained through process-based hydrological modelling. Although the observed associations between discharge, precipitation, and temperature trends revealed consistent and physically plausible patterns, they do not establish causal relationships.

5 Conclusions

This study analyzed hydrometeorological trends for 85 karst spring catchments across the wider Alpine region over the period 2003–2022 to assess recent trend patterns in spring hydrographs with a focus on relating them to hydroclimatic controls and karst-system properties. The results show that recent changes in spring discharge are characterized more strongly by seasonal flow redistribution than by long-term annual trends, although negative annual mean discharge trends are more frequent than positive trends. Winter discharge shows the most consistent signal, with predominantly positive trends across all discharge regimes, although their magnitude varies. Low-flow trends, as well as winter and spring discharge trends, show a clear association with elevation, becoming increasingly positive with higher mean catchment elevation and reflecting changes in snow dynamics, with changes in precipitation likely contributing as well.

The strongest contrast occurs between the winter-pluvial regime in the peri-Alpine region (PC1) and the snow-influenced regimes in the core Alpine region (PC2, PC3, and PC4). Springs in the peri-Alpine region tend toward increasing seasonality, with mostly decreasing spring and summer discharge and increasing winter discharge. Seasonal changes are accompanied by decreasing low-flow and increasing high-flow magnitudes. These patterns are primarily associated with changes in precipitation seasonality and may increase the risk of seasonal water shortages. In contrast, snow-influenced springs in the core Alpine region show decreasing seasonality, characterized by mostly decreasing summer discharge and increasing winter discharge. Low-flow magnitudes generally increase and low-flow occurrence shifts earlier, whereas no consistent high-flow trends are evident across the discharge regimes. This redistribution toward winter and early spring is consistent with warming-induced changes in seasonal snow storage and earlier meltwater contributions. These changes reduce the seasonal contrast characteristic of snow-dominated Alpine catchments and may alleviate water-availability constraints on water supply and hydropower generation during winter. Although these contrasting responses were primarily associated with regime-specific changes in precipitation seasonality and seasonal snow storage, the influence of evapotranspiration could not be clearly isolated.

Changes in hydroclimatic forcing are strongly elevation-dependent, and discharge trend patterns are more clearly structured by discharge regime than by karst-system response type. Even comparatively buffered karst systems may transmit recharge signals over short timescales. Karst-system properties nevertheless modulate spring responsiveness, with trend magnitudes and variability among springs generally decreasing from faster-responding to slower-responding systems, reflecting lower sensitivity to hydroclimatic change with increasing system buffering.

These findings demonstrate that Alpine karst springs respond clearly but heterogeneously to ongoing hydroclimatic change and highlight the importance of month-specific trend analyses for identifying the factors shaping spring discharge trends. The Alps combine rapid hydroclimatic change with the widespread occurrence of karst, making their groundwater systems particularly sensitive to changing recharge conditions. At the same time, the ability of many karst springs to quickly transmit recharge signals makes them valuable regional indicators of hydroclimatic change, while their hydrographs also reflect aquifer-specific storage and drainage processes. Disentangling these influences is therefore essential for understanding ongoing changes in Alpine hydrology and their implications for water resources, human activities, flooding protection, and ecosystems within the Alps and in downstream lowlands. However, long-term spring discharge records remain scarce and are particularly short at higher elevations. Sustained long-term monitoring is therefore needed to better detect changes and attribute them to hydroclimatic and hydrogeological controls in the future.

560 *Code and data availability.* The ALPAKAS dataset used in this study is publicly available at <https://doi.org/10.5281/zenodo.19329693> (Joger et al., 2026b). All code used for the analyses was implemented in R and is publicly available in a dedicated repository at https://github.com/FelixJoger/ALPAKAS_hydroclimatic_analysis (last access: 19 October 2026). R package dependencies and versions are managed and documented using the *renv* package (Ushey and Wickham, 2026).

565 **A Dominant spring groups**

Five dominant spring groups were identified based on the contingency table shown in Fig. A1.

- PC1-C12 (n = 16) combines a winter-pluvial discharge regime with low-storage, fast-draining karst systems and occurs mainly in the Jura Mountains.
- 570 • PC1-C34 (n = 10) combines a winter-pluvial discharge regime with low-storage, moderately draining karst systems and occurs predominantly in the Dinarides.
- PC2-C56 (n = 17) links weakly seasonal discharge behaviour with high-storage, slowly draining karst systems and is broadly distributed across the study region. The high positive standard residual for this combination reflects the distinct character of PC2, for which weak seasonality already indicates substantial hydrological buffering.
- 575 • PC3-C12 (n = 9) combines a nivo-pluvial discharge regime with low-storage, fast-draining karst systems and occurs mainly in the Eastern Alps.
- PC4-C34 (n = 6) combines a nival discharge regime with low-storage, moderately draining karst systems and is associated with high-elevation catchments in the Helveticum and the western part of the Eastern Alps.
- Other combinations (n = 27) indicate less common relationships between discharge regime and karst-system properties and may partly reflect more complex hydrogeological settings. These springs occur mainly in the core Alpine region.

580 The dominant spring groups integrate information from the two individual groupings, providing a more differentiated representation of the interplay between discharge regime and karst-system properties. Given the limited sample size in some dominant spring groups, the corresponding trend patterns are treated as supplementary to the analyses based on Pardé clusters and KarstID classes, which allow trends to be related separately to discharge-regime and karst-system response type. Overall, trends in magnitude (Fig. A2) and timing (Fig. A3) within the dominant spring groups primarily reflect differences among
585 Pardé clusters, while variation associated with KarstID classes is less distinct.

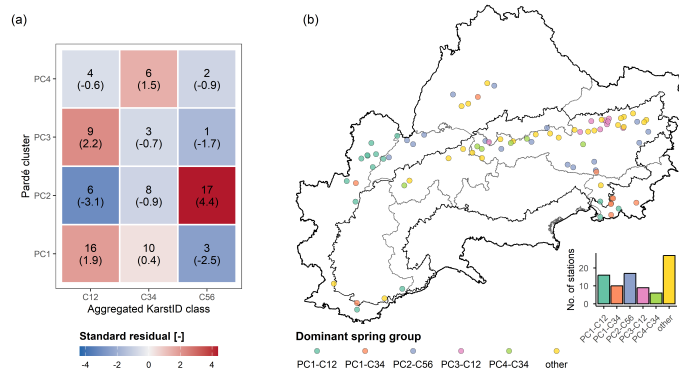


Figure A1: (a) Contingency table showing standardized cell residuals between Pardé clusters and KarstID classes, and (b) spatial distribution of dominant spring groups across the study region. The contingency table reports the absolute number of springs in each group combination, with standardized residuals shown in parentheses. Positive residuals are displayed in red and negative residuals in blue. Administrative borders: © 2018–2025 GADM. Alpine Convention perimeter: Eurac Research and Permanent Secretariat of the Alpine Convention (2025).

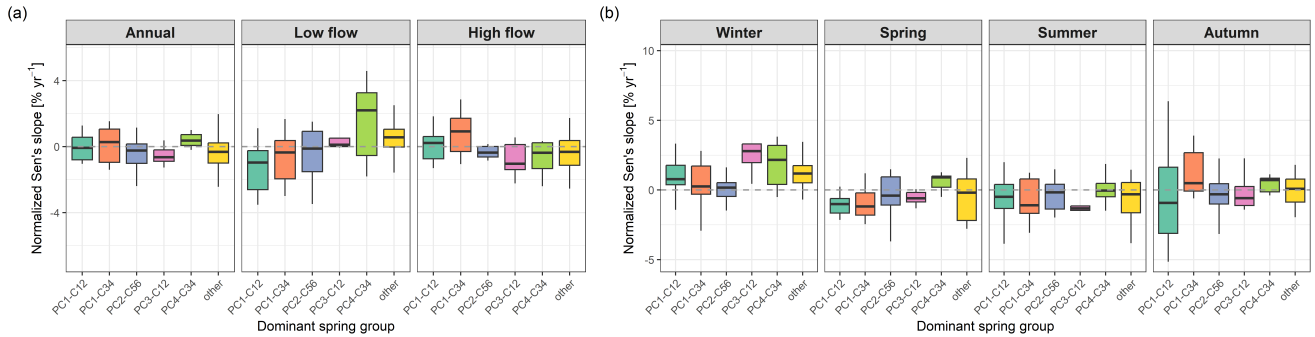


Figure A2: Boxplots showing discharge trends grouped by dominant spring group for (a) annual mean discharge, low flows, and high flows, and (b) seasonal mean discharge.

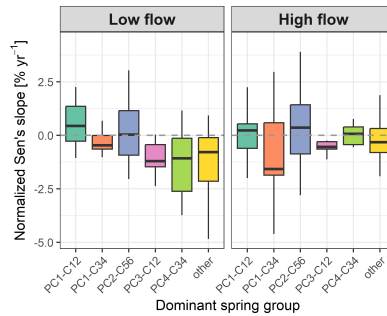


Figure A3: Boxplots showing low-flow and high-flow timing trends grouped by dominant spring group.

B Site-specific classification and trend results

Table B1: Assigned Pardé cluster, aggregated KarstID class, and dominant spring group for all karst springs. Normalized Sen's slopes are reported for annual mean discharge (Q_{mean}), low flows ($Q_{0.1}$), high flows ($Q_{0.9}$), and winter (Q_{DJF}), spring (Q_{MAM}), summer (Q_{JJA}), and autumn (Q_{SON}) discharge, expressed in $\% \text{ yr}^{-1}$. Trend significance is indicated at the $p < 0.05$ (**) and $p < 0.10$ (*) levels.

ALPAKAS ID	Spring name	Pardé cluster	KarstID class	Dominant group	Q_{mean}	$Q_{0.1}$	$Q_{0.9}$	Q_{DJF}	Q_{MAM}	Q_{JJA}	Q_{SON}
AT-0001	Teufelskirche	PC3	C12	PC3-C12	-2.00**	-3.49**	-2.00**	2.74	-2.00	-1.30	-1.42
AT-0002	Waldbachursprung	PC4	C12	other	0.99	5.16**	1.74*	6.12**	1.29	1.12	1.69
AT-0004	Steyernquelle	PC3	C12	PC3-C12	3.52	0.00	2.45	6.66*	4.20	1.91	2.27
AT-0005	Pießling Ursprung	PC3	C12	PC3-C12	-0.63	0.38	-1.39**	1.96	-0.71	-1.15	0.24
AT-0006	Rettenbachquelle	PC3	C12	PC3-C12	-0.20	0.12	0.13	3.30**	-0.18	-1.38	-1.12
AT-0007	Quelle Brunnental	PC2	C12	other	-1.20**	-5.92**	-1.43**	1.13	-2.70	-1.53	-0.94
AT-0008	Miesenbachursprung	PC3	C12	PC3-C12	0.38	4.29*	0.56	2.79	0.06	-0.21	1.64
AT-0009	Gollinger Wasserfall	PC4	C12	other	-0.58	1.01	-0.54	3.46**	-0.42	-1.06	-1.04
AT-0010	Marbachquelle	PC4	C34	PC4-C34	0.19	4.59**	-1.55	3.83**	-0.50	-0.58	0.77
AT-0011	Dachserfall	PC3	C12	PC3-C12	-0.89*	0.51	-0.86	0.44	-0.59	-1.31	-0.85
AT-0013	Schwarzlackenquelle	PC4	C34	PC4-C34	0.56	3.53**	-0.06	2.21**	0.92**	-0.20	1.12
AT-0014	Schreiende Brunnen	PC3	C34	other	-0.04	0.54	-0.14	0.51	0.47	-0.30	0.09
AT-0015	Stubbachquelle	PC2	C56	PC2-C56	-1.02	0.23	-0.61	-0.41	-0.67	-0.82	-0.62
AT-0016	Schwarzbach-Moosquelle	PC4	C56	other	0.14	0.87	0.59	0.32	0.94	0.98	0.85
AT-0018	Lehnbachquellen	PC2	C34	other	1.98**	2.51**	1.34*	4.13**	1.87	1.46	0.81
AT-0020	Blaue Quelle	PC2	C56	PC2-C56	-1.21**	-1.65**	-0.84*	-1.01*	-1.09**	-1.42*	-1.01*
AT-0021	Pulverermühlquelle	PC2	C34	other	1.25	1.70**	1.16	2.62**	1.26	0.90	0.35
AT-0022	Auebachquelle	PC2	C12	other	-1.03**	-0.05	-1.27	1.54*	-2.39	-1.45**	-0.56
AT-0023	Moosbrunnquelle	PC2	C56	PC2-C56	0.72	0.93	1.28	0.52	1.48*	1.48**	1.46
AT-0024	Ursprungquelle (Lehnberg)	PC4	C34	PC4-C34	0.04	1.95**	-0.68	2.13**	0.90	0.13	0.65
AT-0027	Große Mühlquelle	PC2	C12	other	-0.23	0.91	-0.79	2.86*	-2.32	-3.82	-1.43**
AT-0029	Reithbachquelle	PC2	C12	other	-0.96	-0.83	-1.49	1.22	-2.79	0.45	-0.26
AT-0030	Steinbachquelle	PC2	C12	other	-2.39*	0.09	-1.30	1.63**	-2.56	-1.74	-1.95
AT-0032	Union Quelle	PC2	C56	PC2-C56	-0.74*	-0.53	-0.63**	-0.47	-0.41	-0.66**	-1.05**
AT-0034	Lappenbachquelle	PC2	C56	PC2-C56	1.15*	1.50**	1.49	1.62*	0.94	1.08	2.27**
AT-0035	Gerstenbödenquelle	PC4	C34	PC4-C34	-0.20	-1.80	-2.39	-0.18	-0.03	-1.49	-2.79
AT-0036	Goldbachquelle	PC2	C56	PC2-C56	0.07	-0.12	0.01	0.21	-0.15	0.06	0.18
AT-0037	Fidelisquelle	PC4	C56	other	-0.25	0.35	-0.11	0.54*	0.75	-0.52	0.34
AT-0038	Aubachquelle	PC3	C12	PC3-C12	-0.46	0.00	-1.16	9.70**	-0.86	-2.64	-1.37
AT-0039	Marulbachquelle	PC4	C34	PC4-C34	1.01	-1.36	5.29	-0.51	1.27	1.86	-0.39
AT-0041	Hammerbachquelle	PC2	C56	PC2-C56	-1.42	-3.48**	-0.55	-0.70	-2.11**	-1.74	-0.23
AT-0042	Sagtümpel	PC3	C12	PC3-C12	-0.68	1.40	-1.03	3.11*	-0.48	-2.45	-0.58
AT-0043	Wassermannsloch	PC3	C12	PC3-C12	-1.27	-0.06	-2.23**	1.27	-1.32*	-1.46	-0.46
AT-0044	Ödensee-Kaltwassertrichter	PC2	C34	other	0.56**	0.73**	0.52**	1.25**	0.87**	0.09	0.63
AT-0045	Brunnaderquelle	PC2	C56	PC2-C56	1.05*	0.93	1.56**	1.15*	1.12	0.41	1.48**
AT-0046	Schwabeltalquelle	PC3	C34	other	-0.50	0.57	-0.59	1.19	-0.57	-1.95*	1.24
AT-0047	Erbsattelquelle	PC2	C34	other	-0.58	0.00	-0.18	0.52	0.69	0.62	-1.35
AT-0050	Wasseralmquelle	PC3	C56	other	-0.62**	1.53**	-0.91	1.13**	-0.38	-2.25**	0.94
AT-0051	Siebenquellen	PC3	C34	other	-1.53**	1.00	-1.78	0.51	-0.90	-2.91	-0.68
AT-0052	Pfannbauernquelle	PC2	C56	PC2-C56	-0.61*	-0.06	-0.62*	-0.34	-0.81*	-0.97*	-0.72
AT-0053	Alfutzquelle	PC2	C56	PC2-C56	0.57*	1.52**	0.16	1.25**	1.04	0.43	0.46
AT-0057	Maibachl	PC1	C34	PC1-C34	5.56	NA	2.86	9.49**	-0.00	-3.07	8.86
AT-0058	Oswaldquelle	PC2	C56	PC2-C56	0.17	1.02	-0.46	0.99	1.12	0.21	0.67
CH-0003	Siebenbrünnen	PC4	C12	other	0.28	0.72	-0.21	0.72	0.02	0.04	0.51
CH-0004	Source de l'Areuse	PC1	C12	PC1-C12	-0.09	-0.95	-0.73	3.09**	-1.00	-1.12	-2.08
CH-0005	Schlichenden Brünnen	PC4	C12	other	0.18	4.32	0.22	4.64*	-0.19	-0.06	1.32
CH-0006	Source Bossy	PC2	C56	PC2-C56	-0.11	-0.11	-0.01	0.17	-0.58	0.08	-0.31
CH-0010	Source de la Doux	PC2	C56	PC2-C56	-2.39**	-3.18**	-1.80*	-2.15	-3.69**	-1.97**	-2.66**
CH-0011	Quelle Alt St. Johann	PC2	C34	other	0.73**	1.09**	0.51**	1.39**	0.63**	0.64	0.76
CH-0012	Felsenquelle	PC2	C56	PC2-C56	-0.73	-1.51*	-0.35	0.47	-1.23	-1.37	-2.37
CH-0016	Hammerrainquelle	PC2	C56	PC2-C56	-0.10	0.04	-0.20	0.28	0.02	0.85	0.05
CH-0017	Milandre cave stream	PC1	C12	PC1-C12	-1.04	-2.50*	0.49	0.74	-0.78	-0.16	-3.69**
CH-0021	Glarey	PC4	C34	PC4-C34	0.79**	2.46*	0.33	3.52**	1.01*	0.58*	0.86
DE-0001	Bronnbachquelle	PC2	C56	PC2-C56	-2.81*	-3.00	-2.51	-1.47	-2.54*	-1.67	-3.16
DE-0007	Brenzquelle	PC1	C56	other	-2.43*	-1.57*	-1.72	-0.57	-2.48**	-2.25	-1.83
DE-0009	Aachursprung	PC2	C34	other	-1.98*	-1.86	-2.54	-1.61	-2.06	-1.35	-0.68

Continued on next page

ALPAKAS ID	Spring name	Pardé cluster	KarstID class	Dominant group	Q_{mean}	$Q_{0.1}$	$Q_{0.9}$	Q_{DJF}	Q_{MAM}	Q_{JJA}	Q_{SON}
DE-0010	Buchbrunnenquelle	PC2	C56	PC2-C56	-0.23	-0.63**	-0.36	-0.33	-0.38	-0.16	-0.53*
DE-0015	Blautopf	PC1	C34	PC1-C34	-0.97	-0.10	-0.73	-0.00	-1.39	1.09	-0.06
DE-0016	Gallusquelle	PC2	C34	other	-1.68	-2.92**	-0.85	-0.34	-2.52	0.14	-0.83
FR-0003	Source du Doubs	PC1	C12	PC1-C12	0.88	-0.58	0.53	3.28**	0.00	0.15	-0.09
FR-0007	Source d'Arcier	PC1	C12	PC1-C12	-0.85	0.98	-1.30	0.27	-1.01	0.47	-4.69
FR-0009	Source de la Loue	PC1	C12	PC1-C12	-3.52**	-6.98**	-2.83**	-0.34	-4.13**	-3.86*	-5.16**
FR-0011	Source du Lison	PC1	C12	PC1-C12	-0.49	-3.32**	-0.04	1.76**	-1.06	-0.95	-3.09
FR-0013	Source du Verneau	PC1	C12	PC1-C12	-0.78	-3.52	-0.73	1.78**	-2.03	-0.53	-3.21
FR-0014	Sources de la Cuisance	PC1	C12	PC1-C12	-0.19	-2.58*	-0.05	0.98*	-1.56	-0.75	-2.62
FR-0015	Source du Solnan	PC1	C12	PC1-C12	-0.94	-0.96	-0.85	0.82	-0.71	-0.45	-1.65
FR-0019	Source du Groin	PC1	C12	PC1-C12	0.61	-2.66	0.40	3.33**	-0.73	1.44	0.03
FR-0021	Source Bleue (Dortan)	PC1	C34	PC1-C34	1.11*	1.37**	1.17	2.80**	1.19	1.24	-0.08
FR-0024	Source de la Sorgue	PC1	C56	other	-0.32	-0.60	0.07	-0.69	0.06	-0.24	0.39
FR-0027	Source d'Argens	PC1	C34	PC1-C34	0.32	-2.68**	0.69	-2.92	0.28	-1.72	0.92
FR-0028	Source du Caramy	PC1	C12	PC1-C12	0.56	3.50	1.84	-1.42	2.11	3.00	6.37**
FR-0030	Source des Tuves	PC1	C56	other	1.63	2.08	1.31	1.28	2.30	1.20	1.80
FR-0032	Source de la Foux	PC1	C12	PC1-C12	1.28	0.00	0.80	-0.14	0.24	2.00	-0.20
LI-0003	Schneeflucht	PC2	C34	other	-0.83**	0.53	-0.98**	-0.53	-0.40	-1.29**	-0.91
SI-0007	Bohinjska Bistrica	PC2	C12	other	0.10	0.20	-0.31	1.87	0.83	-3.81*	-0.81
SI-0016	Ljubljana	PC1	C12	PC1-C12	-0.04	-1.09	1.29	0.46	-1.97	-1.97	1.75
SI-0022	Ljubija	PC1	C34	PC1-C34	0.24	1.67	1.64	1.67	-0.82	-0.75	1.97
SI-0024	Bistra	PC1	C34	PC1-C34	-0.87	-1.95	0.13	-0.17	-1.17	-1.56	-0.28
SI-0025	Veliki Obrh	PC1	C12	PC1-C12	0.30	-0.89	0.55	0.51	-2.15	-2.55	1.60
SI-0037	Unica	PC1	C34	PC1-C34	0.91	-0.34	1.74	0.53	-1.18	-0.10	2.91
SI-0038	Malenščica	PC1	C34	PC1-C34	-1.40**	-2.99**	-1.05**	-1.27	-2.45**	-1.43	-0.61
SI-0044	Precna	PC1	C34	PC1-C34	-1.14	-1.89*	-0.43	-0.35	-2.10	-2.25	0.06
SI-0052	Hubelj	PC1	C12	PC1-C12	0.89	1.12	1.15	1.30	-0.31	0.38	2.04
SI-0054	Ilirska Bistrica	PC1	C34	PC1-C34	1.54	0.37	2.17*	1.73	-1.94	1.16	3.90
SI-0055	Rižana	PC1	C12	PC1-C12	0.29	-0.32	0.06	0.42	-1.52	-2.65	2.83

C Site-specific associations between discharge and precipitation trends

Fig. C1 shows that, at both annual and seasonal scales, only a small proportion of springs exhibit significant trends in both precipitation and discharge, while significant precipitation trends are most frequent at the annual scale. Overall, discharge and precipitation trends show weak to moderate positive associations ($\rho = 0.29\text{--}0.49$), except for winter. The strongest association occurs in autumn. Similarly, Giese et al. (2025) identified the greatest scatter in winter and the strongest association between discharge and precipitation trends in autumn across a continental dataset of European karst springs, mostly located in France. They interpreted these findings as indicating that spring discharge responded most strongly to precipitation changes during autumn.

Significant discharge trends are generally uncommon in spring, summer, and autumn, whereas winter is characterized by numerous significant discharge increases. Despite predominantly positive winter trends in both discharge and precipitation, no association between their trend magnitudes is evident ($\rho = 0.03$). This supports the interpretation in Sect. 4.2 that increasing winter discharge trends cannot be explained by precipitation trends alone and likely also reflect enhanced meltwater contributions in the core Alpine region. Because the relative importance and seasonal effects of these processes vary with mean catchment elevation, their contribution to discharge changes also varies across the study region. Whereas Sect. 4.2 investigates hydroclimatic controls through monthly trend patterns across Pardé clusters, the present analysis complements it by directly relating discharge and precipitation trends at individual springs.

D Sensitivity of trend estimates to boundary years

Fig. D1 shows that 2022 was among the driest hydrological years, with more than 75 % of springs falling in the 0–25th percentile range for both annual mean and summer discharge. For the hydrological year 2003, a pronounced dry summer is observed, with more than 80 % of springs falling in the 0–25th percentile range. However, 2003 does not stand out as a prominent dry year based on annual mean discharge.

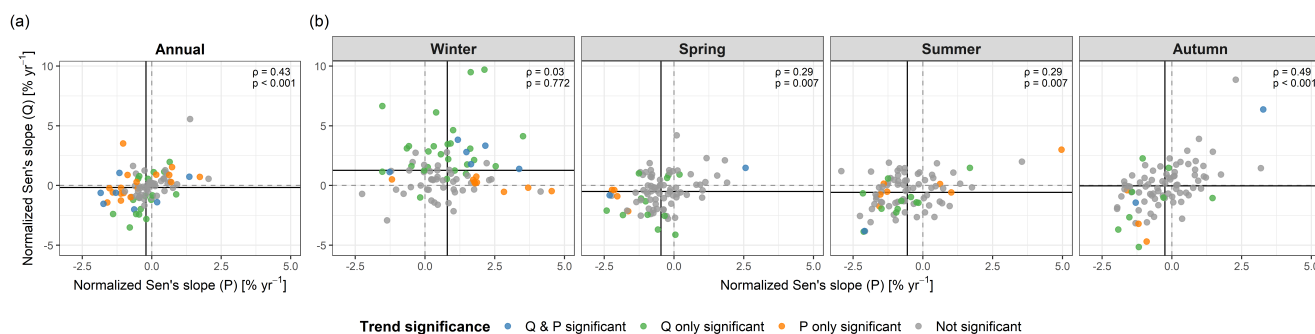


Figure C1: Scatter plots of site-specific discharge and precipitation trends based on (a) annual mean discharge and (b) seasonal mean discharge. Sites are color-coded according to the statistical significance of the discharge and precipitation trends, distinguishing cases in which neither, either one, or both trends are significant at the $p < 0.10$ level. Mean precipitation and discharge are indicated by horizontal and vertical black lines, respectively. The association between discharge and precipitation trend magnitudes is quantified using Spearman's ρ and the corresponding p -value.

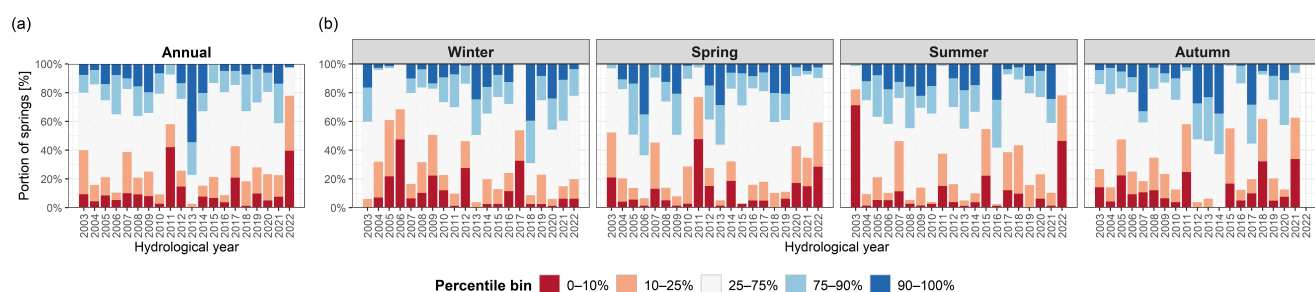


Figure D1: Proportion of springs falling into the percentile bins 0–10 %, 10–25 %, 25–75 %, 75–90 %, and 90–100 %, based on (a) annual mean discharge and (b) seasonal mean discharge. Lower and higher percentiles indicate relatively dry and wet conditions, respectively.

The sensitivity analysis of trend magnitudes (Fig. D2) indicates that the main trend patterns are largely robust to the exclusion of either boundary year, despite some deviations. The strongest differences among periods occur in summer, reflecting the very low summer discharges in both the boundary years 2003 and 2022 (Fig. D1). A similar but less pronounced pattern is observed in spring for PC1 and PC2. For annual mean discharge, the strongest deviations occur for the period 2003–2021, reflecting the exclusion of the very dry year 2022. The comparison between flow timing trends for the reference period and the shortened periods (Fig. D3) shows clear deviations for PC1 and PC2 in both low-flow and high-flow timing.

As both 2003 and 2022 were relatively dry years, excluding 2022 generally tends to produce more positive trends, whereas excluding 2003 tends to result in more negative trends. For most indicators, shifts in median trends are accompanied by similar shifts in the interquartile ranges, indicating that the distribution of trends changes consistently. For most indicators, trends for the reference period 2003–2022 lie between those obtained for 2003–2021 and 2004–2022, suggesting that the selected reference period provides a balanced basis for the trend analysis. Overall, although some trend estimates are sensitive to the exclusion of either the start or end year of the reference period, the dominant patterns within the Pardé clusters remain largely unchanged.

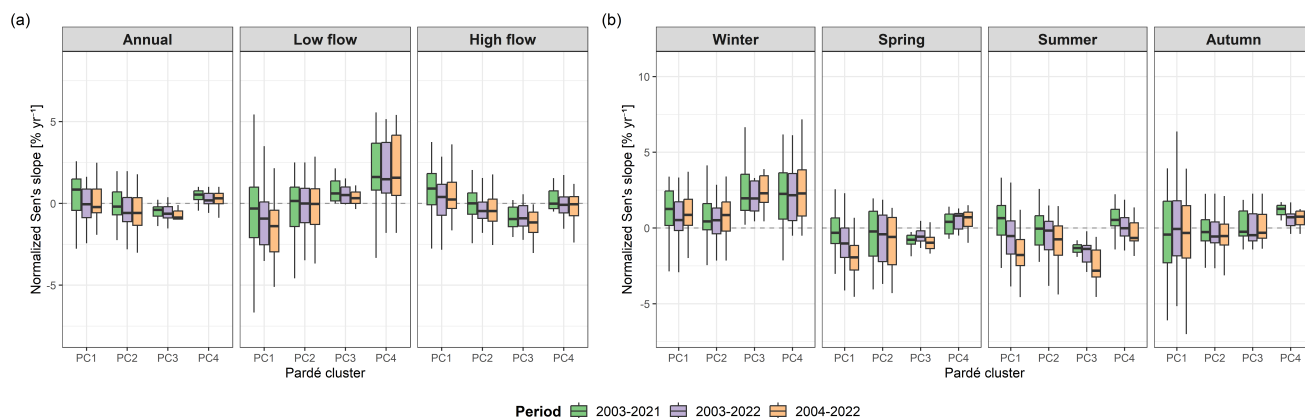


Figure D2: Comparison of trend magnitude results per Pardé cluster for the reference period (purple) and periods excluding the first and last year, respectively (green and orange). (a) Annual mean discharge, low flows, and high flows computed over hydrological years. (b) Seasonal mean discharge.

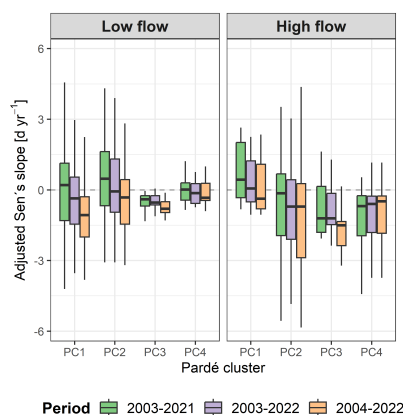


Figure D3: Comparison of trend timing results for low flows and high flows per Pardé cluster for the reference period (purple) and periods excluding the first and last year, respectively (green and orange).

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Competing interests. The authors declare that they have no conflict of interest.

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References

- Bandhauer, M., Isotta, F., Lakatos, M., Lussana, C., Båserud, L., Izsák, B., Szentes, O., Tveito, O. E., and Frei, C.: Evaluation of daily precipitation analyses in E-OBS (v19.0e) and ERA5 by comparison to regional high-resolution datasets in European regions, *Int. J. Climatol.*, 42, 727–747, <https://doi.org/10.1002/joc.7269>, 2022.
- Bard, A., Renard, B., Lang, M., Giuntoli, I., Korck, J., Koboltschnig, G., Janža, M., d’Amico, M., and Volken, D.: Trends in the hydrologic regime of Alpine rivers, *J. Hydrol.*, 529, 1823–1837, <https://doi.org/10.1016/j.jhydrol.2015.07.052>, 2015.
- Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L. M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.-I., Magnusson, J., Marty, C., Morán-Tejeda, E., Morin, S., Naaïm, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S., and Vincent, C.: The European mountain cryosphere: a review of its current state, trends, and future challenges, *The Cryosphere*, 12, 759–794, <https://doi.org/10.5194/tc-12-759-2018>, 2018.
- Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A. P., Merz, B., Arheimer, B., Aronica, G. T., Bilibashi, A., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Fiala, K., Frolova, N., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S., Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Rogger, M., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J., Viglione, A., Volpi, E., Wilson, D., Zaimi, K., and Živković, N.: Changing climate shifts timing of European floods, *Science*, 357, 588–590, <https://doi.org/10.1126/science.aan2506>, 2017.
- Blöschl, G., Blaschke, A. P., Haslinger, K., Hofstätter, M., Parajka, J., Salinas, J., and Schöner, W.: Auswirkungen der Klimaänderung auf Österreichs Wasserwirtschaft – ein aktualisierter Statusbericht, *Österreichische Wasser- und Abfallwirtschaft*, 70, 462–473, <https://doi.org/10.1007/s00506-018-0498-0>, 2018.
- Brunner, M. I., Farinotti, D., Zekollari, H., Huss, M., and Zappa, M.: Future shifts in extreme flow regimes in Alpine regions, *Hydrol. Earth Syst. Sci.*, 23, 4471–4489, <https://doi.org/10.5194/hess-23-4471-2019>, 2019.
- Casati, T., Navarra, A., Filippini, M., and Gargini, A.: Assessing the long-term trend of spring discharge in a climate change hotspot area, *Sci. Tot. Environ.*, 957, 177 498, <https://doi.org/10.1016/j.scitotenv.2024.177498>, 2024.
- Chen, Z., Hartmann, A., Wagener, T., and Goldscheider, N.: Dynamics of water fluxes and storages in an Alpine karst catchment under current and potential future climate conditions, *Hydrol. Earth Syst. Sci.*, 22, 3807–3823, <https://doi.org/10.5194/hess-22-3807-2018>, 2018.
- Cinkus, G., Mazzilli, N., and Jourde, H.: Identification of relevant indicators for the assessment of karst systems hydrological functioning: proposal of a new classification, *J. Hydrol.*, 603, 127 006, <https://doi.org/10.1016/j.jhydrol.2021.127006>, 2021.
- Cinkus, G., Mazzilli, N., and Jourde, H.: KarstID: an R Shiny application for the analysis of karst spring discharge time series and the classification of karst system hydrological functioning, *Environ. Earth Sci.*, 82, 136, <https://doi.org/10.1007/s12665-023-10830-5>, 2023.
- Cornes, R. C., Van Der Schrier, G., Van Den Besselaar, E. J. M., and Jones, P. D.: An ensemble version of the E-OBS temperature and precipitation data sets, *J. Geophys. Res. Atmos.*, 123, 9391–9409, <https://doi.org/10.1029/2017JD028200>, 2018.
- Duethmann, D. and Blöschl, G.: Why has catchment evaporation increased in the past 40 years? A data-based study in Austria, *Hydrol. Earth Syst. Sci.*, 22, 5143–5158, <https://doi.org/10.5194/hess-22-5143-2018>, 2018.
- Dumont, M., Monteiro, D., Filhol, S., Gascoin, S., Marty, C., Hagenmuller, P., Morin, S., Choler, P., and Thuiller, W.: The European Alps in a changing climate: physical trends and impacts, *C. R. Geosci.*, 357, 25–42, <https://doi.org/10.5802/crgeos.288>, 2025.
- Eurac Research and Permanent Secretariat of the Alpine Convention: Alpine Convention perimeter, Permanent Secretariat of the Alpine Convention [data set], <https://doi.org/10.48784/VK93-8P54>, 2025.
- Fan, X., Goeppert, N., and Goldscheider, N.: Quantifying the historic and future response of karst spring discharge to climate variability and change at a snow-influenced temperate catchment in central Europe, *Hydrogeol. J.*, 31, 2213–2229, <https://doi.org/10.1007/s10040-023-02703-9>, 2023.

- Fiorillo, F., Leone, G., Pagnozzi, M., and Esposito, L.: Long-term trends in karst spring discharge and relation to climate factors and changes, *Hydrogeol. J.*, 29, 347–377, <https://doi.org/10.1007/s10040-020-02265-0>, 2021.
- Ford, D. and Williams, P.: Analysis of Karst Drainage Systems, in: *Karst Hydrogeology and Geomorphology*, pp. 145–208, John Wiley & Sons, Ltd, ISBN 978-1-118-68498-6, <https://doi.org/10.1002/9781118684986.ch6>, 2007a.
- Ford, D. and Williams, P.: Karst Hydrogeology, in: *Karst Hydrogeology and Geomorphology*, pp. 103–144, John Wiley & Sons, Ltd, ISBN 978-1-118-68498-6, <https://doi.org/10.1002/9781118684986.ch5>, 2007b.
- Giese, M., Caballero, Y., Hartmann, A., and Charlier, J.-B.: Trends in long-term hydrological data from European karst areas: insights for groundwater recharge evaluation, *Hydrol. Earth Syst. Sci.*, 29, 3037–3054, <https://doi.org/10.5194/hess-29-3037-2025>, 2025.
- Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., and Stoffel, M.: 21st century climate change in the European Alps—A review, *Sci. Tot. Environ.*, 493, 1138–1151, <https://doi.org/10.1016/j.scitotenv.2013.07.050>, 2014.
- Goldscheider, N., Xanke, J., and Liesch, T.: Verbreitung von Carbonatgesteinen und Karstwasserressourcen im Alpenraum, *Grundwasser*, 30, 211–226, <https://doi.org/10.1007/s00767-025-00596-x>, 2025.
- Hamed, K. H. and Ramachandra Rao, A.: A modified Mann-Kendall trend test for autocorrelated data, *J. Hydrol.*, 204, 182–196, [https://doi.org/10.1016/S0022-1694\(97\)00125-X](https://doi.org/10.1016/S0022-1694(97)00125-X), 1998.
- Hannaford, J., Buys, G., Stahl, K., and Tallaksen, L. M.: The influence of decadal-scale variability on trends in long European streamflow records, *Hydrol. Earth Syst. Sci.*, 17, 2717–2733, <https://doi.org/10.5194/hess-17-2717-2013>, 2013.
- Hanus, S., Hrachowitz, M., Zekollari, H., Schoups, G., Vizcaino, M., and Kaitna, R.: Future changes in annual, seasonal and monthly runoff signatures in contrasting Alpine catchments in Austria, *Hydrol. Earth Syst. Sci.*, 25, 3429–3453, <https://doi.org/10.5194/hess-25-3429-2021>, 2021.
- Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., and Weiler, M.: Karst water resources in a changing world: Review of hydrological modeling approaches: KARST WATER RESOURCES PREDICTION, *Rev. Geophys.*, 52, 218–242, <https://doi.org/10.1002/2013RG000443>, 2014.
- Hartmann, A., Gleeson, T., Wada, Y., and Wagener, T.: Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity, *Proc. Natl. Acad. Sci. U.S.A.*, 114, 2842–2847, <https://doi.org/10.1073/pnas.1614941114>, 2017.
- Isotta, F. A., Frei, C., Weilguni, V., Perčec Tadić, M., Lassègues, P., Rudolf, B., Pavan, V., Cacciamani, C., Antolini, G., Ratto, S. M., Munari, M., Micheletti, S., Bonati, V., Lussana, C., Ronchi, C., Panettieri, E., Marigo, G., and Vertačnik, G.: The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data, *Int. J. Climatol.*, 34, 1657–1675, <https://doi.org/10.1002/joc.3794>, 2014.
- Jelen, M., Mikoš, M., and Bezak, N.: Karst springs in Slovenia: trend analysis, *Acta hydrotech.*, pp. 1–12, <https://doi.org/10.15292/acta.hydro.2020.01>, 2020.
- Joger, F., Thinius, P., Chen, Z., Hartmann, A., Goldscheider, N., Liesch, T., Schubert, G., and Broda, S.: ALPAKAS: Alpine hydrographs and catchment attributes for karst springs, *Earth Syst. Sci. Data Discuss.* [preprint], <https://doi.org/10.5194/essd-2026-707>, in review, 2026a.
- Joger, F., Thinius, P., Chen, Z., Hartmann, A., Goldscheider, N., Liesch, T., Schubert, G., and Broda, S.: ALPAKAS: ALPine hydrographs and catchment Attributes for KARst Springs, Zenodo [data set], <https://doi.org/10.5281/zenodo.19329694>, 2026b.
- Kendall, M. G.: Rank correlation methods, Charles Griffin, London, 4 edn., 1975.
- Klotz, D., Miersch, P., Do Nascimento, T. V. M., Fenicia, F., Frank, C., Gauch, M., and Zscheischler, J.: EARLS: a runoff reconstruction dataset for Europe, *Earth Syst. Sci. Data*, 18, 5485–5504, <https://doi.org/10.5194/essd-18-5485-2026>, 2026.
- Kormann, C., Francke, T., Renner, M., and Bronstert, A.: Attribution of high resolution streamflow trends in Western Austria – an approach based on climate and discharge station data, *Hydrol. Earth Syst. Sci.*, 19, 1225–1245, <https://doi.org/10.5194/hess-19-1225-2015>, 2015.

- Kotlarski, S., Gobiet, A., Morin, S., Olefs, M., Rajczak, J., and Samacoïts, R.: 21st Century alpine climate change, *Clim. Dyn.*, 60, 65–86, <https://doi.org/10.1007/s00382-022-06303-3>, 2023.
- 720 Kresic, N. and Bonacci, O.: Spring discharge hydrograph, in: *Groundwater Hydrology of Springs*, pp. 129–163, Elsevier, ISBN 978-1-85617-502-9, <https://doi.org/10.1016/B978-1-85617-502-9.00004-9>, 2010.
- Mangin, A.: *Contribution à l'étude hydrodynamique des aquifères karstiques*, Ph.D. thesis, Université de Dijon, 1975.
- Mann, H. B.: Nonparametric tests against trend, *Econometrica*, 13, 245, <https://doi.org/10.2307/1907187>, 1945.
- Matiu, M., Crespi, A., Bertoldi, G., Carmagnola, C. M., Marty, C., Morin, S., Schöner, W., Cat Berro, D., Chiogna, G.,
 725 De Gregorio, L., Kotlarski, S., Majone, B., Resch, G., Terzago, S., Valt, M., Beozzo, W., Cianfarra, P., Gouttevin, I.,
 Marcolini, G., Notarnicola, C., Petitta, M., Scherrer, S. C., Strasser, U., Winkler, M., Zebisch, M., Cicogna, A., Cremonini,
 R., Debernardi, A., Faletto, M., Gaddo, M., Giovannini, L., Mercalli, L., Soubeyroux, J.-M., Sušnik, A., Trenti, A., Urbani,
 S., and Weilguni, V.: Observed snow depth trends in the European Alps: 1971 to 2019, *The Cryosphere*, 15, 1343–1382,
<https://doi.org/10.5194/tc-15-1343-2021>, 2021.
- 730 Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., and Martius, O.: River runoff in Switzerland in a changing
 climate – changes in moderate extremes and their seasonality, *Hydrol. Earth Syst. Sci.*, 25, 3577–3594, <https://doi.org/10.5194/hess-25-3577-2021>, 2021a.
- Muelchi, R., Rössler, O., Schwanbeck, J., Weingartner, R., and Martius, O.: River runoff in Switzerland in a changing
 climate – runoff regime changes and their time of emergence, *Hydrol. Earth Syst. Sci.*, 25, 3071–3086, <https://doi.org/10.5194/hess-25-3071-2021>, 2021b.
 735
- Pardé, M.: *Fleuves et Rivières*, Armand Colin, Paris, 1933.
- Patakamuri, S. K. and O'Brien, N.: modifiedmk: Modified versions of Mann Kendall and Spearman's Rho trend tests,
<https://CRAN.R-project.org/package=modifiedmk>, r package version 1.6, 2021.
- Schürch, M., Sinreich, M., and Kozel, R.: Grundwasserregime an Quellen – Typisierung für die Schweiz, *Aqua & Gas*, 12,
 740 14–22, <https://www.bafu.admin.ch/dam/de/sd-web/6gXlnYIGnMok/grundwasserregime-quellen-2016.pdf>,
 last access: 24 August 2026, 2016.
- Seelig, M., Seelig, S., Vremec, M., Wagner, T., Briemann, H., Eybl, J., and Winkler, G.: Quantitative classification of spring
 discharge patterns: A cluster analysis approach, *Hydrol. Process.*, 38, e15 326, <https://doi.org/10.1002/hyp.15326>, 2024.
- Sen, P. K.: Estimates of the regression coefficient based on Kendall's Tau, *J. Am. Stat. Assoc.*, 63, 1379–1389, <https://doi.org/10.1080/01621459.1968.10480934>, 1968.
 745
- Somers, L. and McKenzie, J.: A review of groundwater in high mountain environments, *WIREs Water*, 7, <https://doi.org/10.1002/wat2.1475>, 2020.
- Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., Van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M., and Jódar,
 J.: Streamflow trends in Europe: evidence from a dataset of near-natural catchments, *Hydrol. Earth Syst. Sci.*, 14, 2367–2382,
 750 <https://doi.org/10.5194/hess-14-2367-2010>, 2010.
- Thinius, P., Joger, F., Liesch, T., and Goldscheider, N.: Automated karst spring catchment approximation for discharge
 modelling, *EGUsphere* [preprint], <https://doi.org/https://doi.org/10.5194/egusphere-2026-5402>, 2026.
- Toran, L., Baraza, T., Özdemir Çallı, K., Finegan, C. R., Hasenmueller, E. A., Nyquist, J., Sarker, S. K., and Spellman,
 P.: Long-Term Discharge Records from United States and European Karst Springs: Data Limitations in Trend Analysis,
 755 *Groundwater*, 64, 634–649, <https://doi.org/10.1111/gwat.70093>, 2026.
- Ushey, K. and Wickham, H.: renv: Project Environments, <https://doi.org/10.32614/CRAN.package.exactextractr>, version 1.2.2,
 2026.
- Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor,
 M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., and Woods, R.: Climate change
 760 and mountain water resources: overview and recommendations for research, management and policy, *Hydrol. Earth Syst.*
Sci., 15, 471–504, <https://doi.org/10.5194/hess-15-471-2011>, 2011.

- Vremec, M., Seelig, M., Seelig, S., Collenteur, R., Haslinger, K., Wagner, T., Eybl, J., and Winkler, G.: Trend analysis of Alpine spring discharge: Interplay between climate and discharge characteristics, *Sci. Tot. Environ.*, 993, 179 875, <https://doi.org/10.1016/j.scitotenv.2025.179875>, 2025.
- 765 Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., and Birk, S.: Impacts of climate change on stream flow and hydro power generation in the Alpine region, *Environ. Earth Sci.*, 76, 4, <https://doi.org/10.1007/s12665-016-6318-6>, 2017.
- Wang, F., Shao, W., Yu, H., Kan, G., He, X., Zhang, D., Ren, M., and Wang, G.: Re-evaluation of the power of the Mann-Kendall test for detecting monotonic trends in hydrometeorological time series, *Front. Earth Sci.*, 8, 14, <https://doi.org/10.3389/feart.2020.00014>, 2020.