Hydrol. Earth Syst. Sci., 29, 3037–3054, 2025
https://doi.org/10.5194/hess-29-3037-2025

Hydrology and Earth System Sciences
Open Access

Trends in long-term hydrological data from European karst areas: insights for groundwater recharge evaluation

Markus Giese[1,2], Yvan Caballero[1,2], Andreas Hartmann[3], and Jean-Baptiste Charlier[1,2]

[1]BRGM, Univ. Montpellier, Montpellier, France
[2]G-eau, UMR 183, INRAE, CIRAD, IRD, AgroParisTech, Institut Agro, BRGM, Montpellier, France
[3]Institute for Groundwater Management, TU Dresden, Dresden, Germany

Correspondence: Markus Giese (markus.giese@gu.se)

Received: 5 July 2024 – Discussion started: 15 July 2024
Revised: 27 March 2025 – Accepted: 1 April 2025 – Published: 17 July 2025

Abstract. Long-term observations of spring discharge provide an alternative for estimating the evolution of groundwater resources based on observational data at the catchment scale. Karst springs can be found in large parts of Europe, covering all climate zones of the mid-latitudes. Continuous spring discharge measurements are holistic signals, representing both fast and slow flow components, typical of karst environments. Due to relatively short response times, karst systems are pivotal in improving our understanding of the impact of climate change on groundwater resources. This study analyses observational data (precipitation, temperature, and discharge) from over 50 springs distributed across Europe (AT, FR, GB, SI), offering a continental perspective on groundwater resource changes in karst areas. The work focuses on two periods spanning 20 and 40 years, aiming to detect possible accelerations or moderations in trends over time. For both periods, trend analyses of the observational data were conducted using the Mann–Kendall test and Sen's slope on full time series as well as seasonal data. Additionally, potential process changes were examined through trends in high and low flow values. Structural differences among karst systems were accounted for using two indices related to storage and inertia of the system, which were used to (i) highlight structural differences and (ii) classify karst systems accordingly. The results show that the sensitivity of karst aquifers to climate change is not controlled by their degree of karstification. Long-term trends in spring discharge observed in this study align with the general patterns of river discharge found in the literature. However, the behaviour during the last 20 years diverges from these historical patterns. In this most recent period, increasing temperatures play a more significant role in the evolution of spring discharge than changes in precipitation. These findings are contextualized with consideration of indirect drivers, such as changes in land use or land cover, specific regional conditions, and shifts in groundwater recharge and storage processes. Together, they offer valuable insights for assessing groundwater recharge in the past and in the future.

1 Introduction

The impact of global change on freshwater availability and quality is mostly associated with changes in hydrological extremes, for example droughts or floods (e.g. Blöschl et al., 2019; Vicente-Serrano et al., 2019; Tramblay et al., 2020; Lorenzo-Lacruz et al., 2022), whereas the future evolution of groundwater recharge – as a key process for sustainable water supply by groundwater – is currently highly uncertain (IPCC, 2021). The complexity and multitude of processes related to groundwater recharge make it highly variable in space and time with interconnections to various drivers (see Moeck et al., 2020; Riedel and Weber, 2020; Barthel et al., 2021). Moreover, the absence of direct spatially distributed measurements of actual recharge complicates the identification of regional trends, even when a comprehensive global data set of groundwater recharge measurements is analysed (Moeck et al., 2020).

Hydroclimatic conditions, e.g. precipitation and temperature, are generally considered primary drivers of land surface water fluxes, making groundwater recharge highly susceptible to climate change (Mohan et al., 2018). Over recent decades, however, human activities – such as increased water consumption and land use changes (closely connected to net increases in evaporation) – have exerted a growing influence on groundwater recharge (e.g. Haas and Birk, 2019). In many parts of Europe, impacts of anthropogenic activity are comparable to those caused by changing hydroclimatic conditions (Teuling et al., 2019), reaching the point where they prevail over changes in natural land surface fluxes (Riedel and Weber, 2020). Approaches for groundwater recharge modelling allow for the consideration of these changing conditions on a larger scale (e.g. Lanini and Caballero, 2021; Martinsen et al., 2022; Seidenfaden et al., 2023). However, they have the disadvantage that a validation of derived values with in situ observations is generally not possible. This leaves hydrological time series based on observations as an essential reference for assessing long-term changes in water resources.

Long-term spring discharge observations provide an alternative means of estimating groundwater resources evolution at the catchment scale. Karst aquifers, in particular, are of significant interest due to their unique properties, closely related to soluble (carbonate) rocks, generating a hierarchical organized groundwater drainage network over large areas (e.g. Palmer, 1991; Ford and Williams, 2007). Therefore, continuous measurements of karst spring discharge offer a holistic output signal of the aquifer system integrating the various processes that transform the recharge signal as it propagates through the system to the outlet. Unlike most other types of aquifer systems, groundwater flow in karst areas is thus highly influenced by differences in hydraulic properties (channels/conduits vs. fractured/porous matrix) and needs to be divided into concentrated and diffuse processes (e.g. Smart and Hobbs, 1986). Hydraulic properties such as permeability, porosity, and storativity govern the time response of these systems. The storativity of a karst aquifer, which refers to the ability of the aquifer to store and release water, plays a crucial role in the response of spring discharge to recharge events. The interaction between conduit and matrix flow components introduces a time lag in the aquifer's response to recharge referred to as the system's inertia.

Changes in fast flow dynamics make it potentially possible to detect the impact of groundwater recharge on water resources. Consequently, spring discharge can be used as a robust regional climate indicator (Fiorillo et al., 2021), and karst aquifers, due to their sensitivity, can be sentinels of global change (Binet et al., 2020, 2022).

In Europe, karst outcrops cover an absolute area of approximately $2.17 \times 10^6\,\mathrm{km}^2$, accounting for 21.8 % of the continent's total area (Goldscheider et al., 2020). The contribution of water from karst areas to national freshwater supply varies widely, ranging from 5 % to 50 % (Hartmann et al., 2014), making karst aquifers, together with alluvial formations, the most important source of freshwater (Bakalowicz, 2005). For water management and ecological flow maintenance downstream, low flow characteristics in karst systems and their development are of special importance. Less in focus are high flow characteristics even though flash floods in karst systems can pose hazards to human life (Maréchal et al., 2008).

Most of the global karst springs with long observation records are located in Europe (Olarinoye et al., 2020). While spring discharge analysis is a common tool for characterizing karst systems, it can also be used to analyse changes in hydroclimatic conditions or recharge values. Over a long period, European karst spring discharge appears to have declined due to rising temperatures, and the consequent reduction in snow contribution (Chen et al., 2018; Jódar et al., 2020; Lorenzi et al., 2022; Petitta et al., 2022; Fan et al., 2023), and increased evapotranspiration (Leone et al., 2021) rather than changes in precipitation patterns. The latter only seems to have an impact on drought frequency (Leone et al., 2021) and peak discharge (Fan et al., 2023). Additionally, other factors such as land use or land cover changes, e.g. large-scale forest disturbance (Kovacic et al., 2020; Vilhar et al., 2022), changes in intensification of agricultural use (Palacios-Cabrera et al., 2022), and water abstraction (Charlier et al., 2015), can obscure the long-term effects of climate change on spring discharge. Notably, studies on Italian karst springs have highlighted a strong correlation between spring discharge and large-scale atmospheric circulations, e.g. North Atlantic Oscillation (NAO), with negative (winter) NAO values having correlated with increased spring discharge since around 2008 (De Vita et al., 2012; Fiorillo and Guadango 2012; Fiorillo et al., 2015, 2021). However, the influence of various large-scale atmospheric circulations results in complex periodicities ranging from biennial to multidecadal cycles (De Vita et al., 2012). Accordingly, the impact on spring discharge is high, accounting for a variability of roughly 30 %. Differences in the response of karst systems have been detected, which are generally explained by variations in storativity or inertia of the karst system (Fiorillo and Guadango 2012; Fiorillo et al., 2021; Lorenzi et al., 2022).

Thus, changing hydroclimatic conditions are expected to increasingly threaten freshwater resources in most karst areas in Europe by reducing groundwater recharge until the end of this century (Hartmann et al., 2017). Although the long-term impact on groundwater resources in other systems is still highly uncertain, it is most likely that climate change will affect karst water resources and therefore negatively affect the reliable water supply of millions of people. In this context, this paper presents a continental overview of changes in groundwater resources in karst areas over the past decades, based on more than 50 springs distributed across Europe. This study is a multi-decadal trend analysis of hydroclimatic observational data for European karst systems and designed to answer the following research questions.

- Does discharge from European karst areas change uniformly over time or is it possible to detect regional patterns?

– Does variability in discharge have an impact on low and high flow conditions?

– Is it possible to identify karst systems, based on storage-related indices, that exhibit either vulnerability or resilience to climate change?

To answer the research questions raised above, this study examines long-term discharge trends in 58 European karst springs. The analysis focuses on two time periods: a 40-year period to capture long-term trends and a 20-year period to assess recent changes. Trends in discharge, extreme flow conditions, precipitation, and temperature are evaluated to identify potential drivers of change. Additionally, indices related to storativity and system inertia are used to explore the influence of groundwater dynamics. Finally, trends in the investigated indices are discussed in relation with known hydroclimatic changes on surface waters, seasonality, and with consideration of indirect drivers, such as changes in land use or land cover, specific regional conditions, and shifts in groundwater recharge and storage processes.

2 Data and methods

Karst outcrops drained by major karst springs are widespread across Europe (Fig. 1; Chen et al., 2017), spanning all climate zones of the mid-latitudes. Hydroclimatic conditions, combined with geological history, play an important role in the evolution of karst aquifers resulting in a complex pattern of systems on a continental scale. To evaluate the impact of changing climatic conditions on different types of karst systems, this study examines publicly available spring discharge data from multiple European countries. To assess potential climate change impacts on karst groundwater resources over recent decades, the following method was applied. Long-term trends in karst spring discharge were analysed for all European springs with time series meeting the requirements outlined in Sect. 2.1. The assessment focused on two different time periods – described herein – following the maxim of (a) having as many discharge records as possible among the available data and (b) comparing results between two different periods in order to identify any possible acceleration or moderation of changes. The first period spans 40 years (starting on 1 January 1982) to capture long-term trends, while the second covers a shorter period of 20 years (starting date: 1 January 2002). The shorter period enables the examination of a shorter time frame, comparable to those describing Italian karst springs (e.g. Fiorillo et al., 2021). Changes were evaluated using the Mann–Kendall test and Sen's slope computation (Sect. 2.3) for both monthly spring discharge and annual extremes, expressed as different quantiles, namely the 10th and 90th percentile. Additionally, trends in monthly precipitation and temperature were computed to identify changes in the input signal of the systems. To further investigate the influence of groundwater dynamics on observed trends, two specific indices – related to storativity and inertia (Sect. 2.1.1 and 2.1.2) – were calculated for each period.

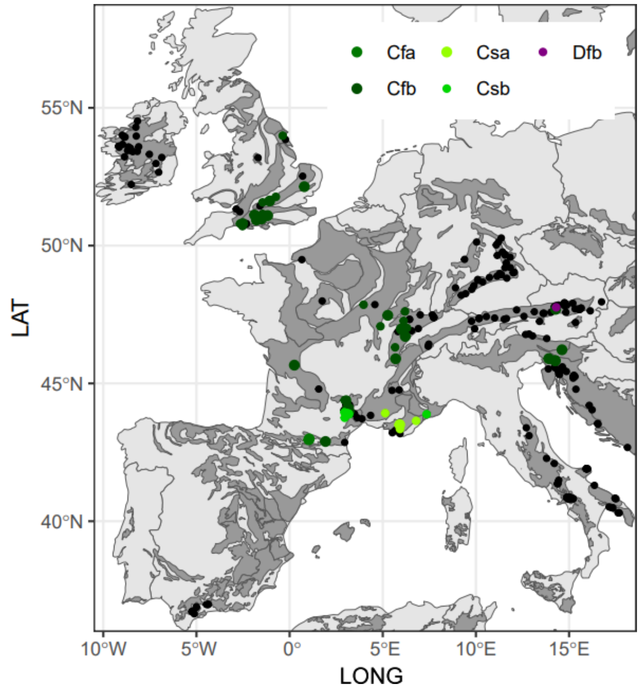

Figure 1. Karst spring location (black dots) according to the WOKAS database (Olarinoye et al., 2020) and carbonate rock outcrop (dark area) in Europe according to WoKaM (Chen et al., 2017). Springs used in this analysis are coloured. Colours indicate the climate zone according to the Koeppen–Geiger classification (1986–2010) in Table 1.

2.1 Karst spring discharge

Spring discharge data were obtained from the World Karst Spring Hydrograph dataset (WOKAS; Olarinoye et al., 2020) and the French national database Hydroportail (https://www.hydro.eaufrance.fr/, last access: 25 June 2025). The WOKAS dataset aggregates spring discharge data from national agencies and time series collected by various research groups worldwide. In both databases, spring discharge is interpreted broadly, meaning measurements may have been taken downstream of the spring itself. From both datasets, all time series meeting the minimum requirements for the two periods – 20 years (starting on 1 January 2002) and 40 years (starting on 1 January 1982) – were selected. The minimum requirements were (a) continuous daily measurements and (b) less than 10 % missing data over the respective 20- and 40-year periods. No pre-processing, such as interpolation of missing data, was performed prior to the analysis. In total, 54 springs from four countries satisfied the requirements for the shorter period, and 22 springs from four countries met the criteria for the longer period (Fig. 1). Detailed information on spring names, time series, and locations is provided in Table 1. Note

Table 1. Overview of the European karst springs used in this analysis. Climate zones are according to the Koeppen–Geiger classification (1986–2010). Mean discharge is calculated from the daily values either of the 40-year period or for shorter time series of the 20-year period. Country codes: Austria (AT), France (FR), United Kingdom of Great Britain (GB), Slovenia (SI).

Country	Name	Lat	Lon	Climate zone	Q_{mean} ($m^3 s^{-1}$)	40y	20y
AT	Piessling Ursprung	47.69	14.28	Cfb	2.15	X	0
AT	Rettenbachquelle	47.76	14.31	Dfb	1.06	0	X
FR	Aiguebelle	43.93	3.06	Csb	0.12	0	X
FR	Aliou	42.99	1.05	Cfa	0.43	X	0
FR	Arcier	47.27	6.12	Cfb	1.14	0	X
FR	Argens	43.50	5.91	Csa	0.38	X	X
FR	Baget	42.96	1.03	Cfa	0.45	X	0
FR	Balastière	43.97	3.03	Csb	0.07	0	X
FR	Barbade	44.18	3.09	Cfb	0.08	0	X
FR	Bastide	44.30	3.07	Cfb	0.03	0	X
FR	Bèze	47.47	5.27	Cfb	3.81	X	X
FR	Bleue Dortan	46.31	5.66	Cfb	1.21	0	X
FR	Boundoulaou	44.07	3.05	Cfb	0.23	0	X
FR	Cainea	43.88	7.35	Csb	0.03	0	X
FR	Caramy	43.35	5.92	Csa	0.06	0	X
FR	Ceras	43.75	2.96	Csb	0.99	0	X
FR	Cernon	43.96	3.15	Cfb	0.19	0	X
FR	Doubs	46.71	6.21	Cfb	1.89	X	X
FR	Dragonnière	43.95	2.94	Csb	0.08	0	X
FR	Duc	44.40	3.08	Cfb	0.04	0	X
FR	Durzon	43.99	3.26	Cfb	1.52	0	X
FR	Esperelle	44.12	3.21	Cfb	1.01	0	X
FR	Font de Champdamoy	47.61	6.19	Cfb	2.33	0	X
FR	Fontaine de Vaucluse	43.92	5.13	Csa	15.51	0	X
FR	Fontestorbes	44.89	1.93	Cfb	1.88	X	X
FR	Fosse Dionne	47.86	3.97	Cfb	0.30	0	X
FR	Fousette	43.91	3.12	Csb	0.17	0	X
FR	Gloriette	43.91	3.18	Csb	0.09	0	X
FR	Groin	45.89	5.69	Cfb	3.15	X	X
FR	Ladoix	47.07	4.88	Cfb	0.22	0	X
FR	Ladoux	44.08	3.06	Cfb	0.27	0	X
FR	Lestang	44.41	3.02	Cfb	0.21	0	X
FR	Lison	46.96	6.01	Cfb	5.07	X	X
FR	Loue	47.01	6.30	Cfb	9.56	0	X
FR	Mayrinhac	44.39	2.95	Cfb	0.13	0	X
FR	Mouline	44.99	1.05	Cfb	0.50	0	X
FR	Segala	44.36	3.02	Cfb	0.17	0	X
FR	Sorgue	43.88	3.19	Csb	1.03	0	X
FR	Touvre	45.66	0.26	Cfb	13.05	X	X
FR	Tuves	43.64	6.79	Csa	0.06	0	X
FR	Verneau	46.98	6.00	Cfb	0.44	X	X
GB	Avon	50.93	−1.07	Cfb	15.75	X	X
GB	Brett	52.14	0.79	Cfb	0.13	X	X
GB	Cheriton	51.09	−1.18	Cfb	0.69	X	X
GB	Ewelme	51.62	−1.07	Cfb	0.04	X	X
GB	Hooke	50.80	−2.66	Cfb	0.02	0	X
GB	Manor Farm Brook	51.57	−1.45	Cfb	0.01	0	X
GB	S. Winterbourne	50.71	−2.53	Cfb	0.12	0	X
GB	Sydling Water	50.8	−2.52	Cfb	0.20	X	X
GB	Test Broadlands	50.97	−1.50	Cfb	10.88	X	X
GB	Test Chilbolton	51.15	−1.45	Cfb	5.59	0	X
GB	Wendover Spring	51.77	−0.74	Cfb	0.09	0	X
GB	West Beck	53.99	−0.37	Cfb	2.38	0	X
GB	Wylye	51.10	−1.88	Cfb	4.00	X	X
SI	Hubelj-Ajdovščina I	45.90	13.91	Cfb	2.80	X	X
SI	K. Bistrica-Kamnik	46.22	14.62	Cfb	7.04	X	0
SI	Malenščica-Malni	45.82	14.25	Cfb	6.15	X	X
SI	Unica-Hasberg	45.83	14.26	Cfb	20.89	X	X

that nine time series from French springs start during the first or the second year, while all other time series were aligned to start on 1 January and end 20 or 40 years later (on 31 December 2021). For Austrian springs, data were only available until the end of 2019.

Most of the springs are located within the temperate oceanic climate zone (Cfb) covering large parts of western Europe. Springs in other climate zones include those in the Pyrenees (Cfa – warm temperate climate), parts of Austria (Dfb – humid continental climate) and in southern France (Csa/Csb – Mediterranean climate). Some of the investigated karst areas, particularly in Austria and the Grands Causses region in southern France, are located along climate zone boundaries.

Monthly mean discharge was calculated for each spring (Table 1) and used in the trend analysis. Additionally, trends were calculated for the annual minimum and maximum flow. These values were derived by aggregating discharge below the 10th quantile (Q10) and above the 90th quantile (Q90), using the R package *stats*. In addition, the karst systems were classified based on two indices derived from the daily discharge time series. Karst systems are generally classified according to flow patterns (e.g. Mangin, 1975; Quinlan and Ewers, 1985), which are a combination of dominant recharge processes, storativity and flow dynamics within different karst system compartments (Smart and Hobbs, 1986). All these factors are strongly dependent on hydraulic properties, which are, in turn, closely related to the maturity or degree of karstification of the system. To classify the springs based on dominating discharge component and storativity, two commonly used indices were computed.

Firstly, to assess the storage capacity of karst systems, daily discharge was filtered to separate quick and slow flow components and therefore compute the baseflow index (BFI). Traditionally, the slow flow component is interpreted as baseflow (Smakhtin, 2001). In karst hydrology, it is often conceptually described as the outflow of a single reservoir as a function of the active storage volume (Maillet, 1905). Numerous methods for baseflow separation exist (e.g. Sloto and Crouse, 1996; Rutledge, 1998; Piggott et al., 2005; Eckhardt, 2005). Following the proposal of Ladson et al. (2013); here the "standard approach" by Lyne and Hollick (1979) was selected, implemented in the R package *BFI* (Ladson et al., 2013). This method can be described as a smoothing algorithm using a one-parameter recursive digital filter. The filter coefficient α influences the degree of smoothing and sets a threshold to separate high-frequency (quick) flows from low-frequency (slow, baseflow) components. The baseflow volume and therefore BFI is sensitive to the filter coefficient α, which ranges between 0.9 and 0.98. Here, α was set to 0.925 for all springs since the analysis focuses only on the evolution of the baseflow and not a quantitative comparison between different springs or periods. After splitting the time series into quick flow and baseflow components, the BFI is calculated as the ratio between baseflow and total discharge. In the case of larger gaps, the values are calculated individually for the segments, and the BFI for the entire time series is the weighted average of the segments.

Secondly, to describe the inertia of karst systems, the memory effect was calculated. This is determined using a threshold of 0.2 in the autocorrelation function below which the signal is considered indistinguishable from noise (Mangin, 1984). The memory effect is widely used to characterize storativity in karst systems and to compare response times across systems (e.g. Larocque et al., 1998; Padilla and Pulido-Bosch, 1995; Fiorillo and Doglioni, 2010; Dubois et al., 2020; Cinkus et al., 2021; Bailly-Comte et al., 2023). One autocorrelation function was calculated for each period and spring using the R package *stats.*

2.2 Precipitation and temperature

Precipitation and temperature data were obtained from the daily gridded observational dataset for Europe (E-OBS; Cornes et al., 2018). The E-OBS dataset provides hydroclimatic data on a 0.1° regular grid, based on the interpolation of observations from a network of European meteorological stations. The dataset currently spans the period between 1950 and 2022. For each karst spring, climate variables were extracted based on the geographic coordinates of the spring. However, for karst springs with catchments larger than the cell size or high topographical gradient, this approach might not fully capture local variability. Additionally, in areas with high spring density, one single grid cell may represent the hydroclimatic conditions for multiple springs.

For trend analysis, daily precipitation values were summed and daily temperature values were averaged to calculate monthly and seasonal values. Although the study encompasses a range of climate zones across Europe, standardized meteorological seasons (winter: DJF, spring: MAM, summer: JJA, and autumn: SON) were used for consistency.

2.3 Trend analysis

The Mann–Kendall test (Kendall, 1948; Mann, 1945) is a widely used method for trend analysis of observational data and climatic indices. This includes analysis of the E-OBS dataset, which has been evaluated at various temporal resolutions such as monthly, seasonal, and annual scales (e.g. Peña-Angulo et al., 2020). However, to compare the observational data at the location of the springs over the two defined periods, the Mann–Kendall test was applied to spring discharge and hydroclimatic variables. The rank-based, non-parametric Mann–Kendall test assesses the significance of monotonic trends by evaluating differences between earlier and later measurements in the time series. As a non-parametric test, it is suitable for data with non-normal distributions and is, therefore, commonly applied in hydrological studies. Here, the modified Mann–Kendall test after Hamed and Rao (1998) was used, which includes a variance correction approach to account for autocorrelation in the time series. Specifically, the test statistic is computed as the sum of the signs of differences between all pairs of data points, with the variance adjusted using a variance inflation factor derived from the autocorrelation structure. For a detailed explanation, readers are referred to Hamed and Rao (1998). To address sensitivity to confidence levels, two significance thresholds were used: p values of 5 % and a more relaxed threshold of 10 %. In addition, Sen's slope (Sen, 1968) was calculated to determine the magnitude and direction of the trend, with positive values indicating increasing trends and negative values indicating decreasing trends. The Mann–Kendall test and Sen's slope were chosen for their widespread use in monotonic trend analyses in both climatic and hydrological contexts. They have the advantage of being independent of the data distribution, making them particularly suitable for non-normal data, such as monthly discharge from karst springs (e.g. Fiorillo et al., 2021). Both statistical tests are included in the R package *modifiedmk* (Hamed and Rao, 1998).

3 Results

3.1 Trends in monthly spring discharge and climate variables

Only six of the analysed springs exhibit significant changes in discharge over the past 40 years (Fig. 2a). Among these, the four springs with decreasing trends show higher significance (at the 5 % probability level) compared to the two springs with increasing trends (at the 10 % probability level). With the exception of two springs, all springs with 40-year discharge records are located in the temperate climate zone (Cfb). Of the exceptions, one spring is situated in the Mediterranean climate zone (Csa) and the other in the humid subtropical climate zone (Cfa). Both show decreasing spring discharge. The latter spring (Fontestorbes) drains a mountainous catchment in the Pyrenees. The other two springs with decreasing spring discharge (Lison and Verneau) are located in the French Jura Mountains, which is also a mountainous region. In contrast, Spring Piessling Ursprung, which drains a karst system on the northern slopes of the Austrian Alps, shows an increasing discharge trend. It is one of the two springs with positive trends, the other being Spring Cheriton in England.

Discharge trends over the past 20 years (Fig. 2b) differ both locally and continentally from the long-term trends. Positive trends are dominant in large parts of Europe. Of the 15 springs with a positive trend, 1 spring is in the Csa and 1 spring in the Csb climate zone, while the remainder are in the Cfb zone. Many of these springs are located in the Grands Causses region, a high plateau under Mediterranean influence in southern France. Conversely, only three springs exhibit negative discharge trends during the 20-year period, distributed across Europe. Importantly, none of the springs that exhibit significant trends over the 40-year period show significant changes during the shorter 20-year period.

Despite the number of springs with significant discharge trends, precipitation remains relatively stable over both periods, with changes occurring only locally (Fig. 2c and d). Over the 40-year period, significant precipitation trends are detected in just six karst areas represented by E-OBS grid cells. Three of these are in southern England near the region of Spring Cheriton, although the grid cell containing the spring itself does not show a significant increase. The only region with a negative precipitation trend is the French Jura Mountains, where two springs with negative discharge are located. Over the last 20 years, the negative precipitation trend in the Jura Mountains has slowed, and no significant changes are detected in this area. Further south, in the Grands Causses region, a decrease in precipitation is observed in the northernmost part of the region but only at a lower significance level. The number of positive trends in UK grid cells also declines, with only one grid cell showing significance at a lower level.

In contrast, air temperature shows a uniform significant increasing trend across Europe over the 40-year period (Fig. 2e). During the last 20 years (Fig. 2f), temperature continues to rise in most spring locations, with the exception of England, where no trends are observed.

3.2 Seasonal changes in monthly spring discharge and climate variables

Spring discharge varies widely among European karst springs (see Table 1). To account for differences in mean discharge, a normalized Sen's slope (seasonal Sen's slope$/Q_{\mathrm{mean}}$) was used to analyse changes in seasonal discharge on the continental scale. In Fig. 3, the top-right and bottom-left corners of each seasonal subplot indicate similar positive and negative Sen's slopes for normalized seasonal discharge (Q) and seasonal precipitation (P) respectively. For simplicity, all locations are summarized in a single plot irrespective of their climatic zones. Based on the results presented in Fig. 2, air temperature was excluded from the seasonal analysis, as its uniform increase across all seasons and springs was not considered a key factor influencing interannual discharge variability.

Overall, significant simultaneous changes in both P and Q are rather rare, occurring at only a small percentage of the springs. Except for one case in summer over the 40-year period, the significant trends in both precipitation and discharge generally follow the same direction. Significant changes in Q are more prevalent, but the direction of these trends varies widely among springs and seasons. Winter is the season with the fewest significant changes in both periods, but it shows the greatest variation in Sen's slopes for both discharge and precipitation trends. Despite this, most springs have positive Sen's slopes, indicating an overall increasing trend in discharge during winter. Precipitation trends in winter, however,

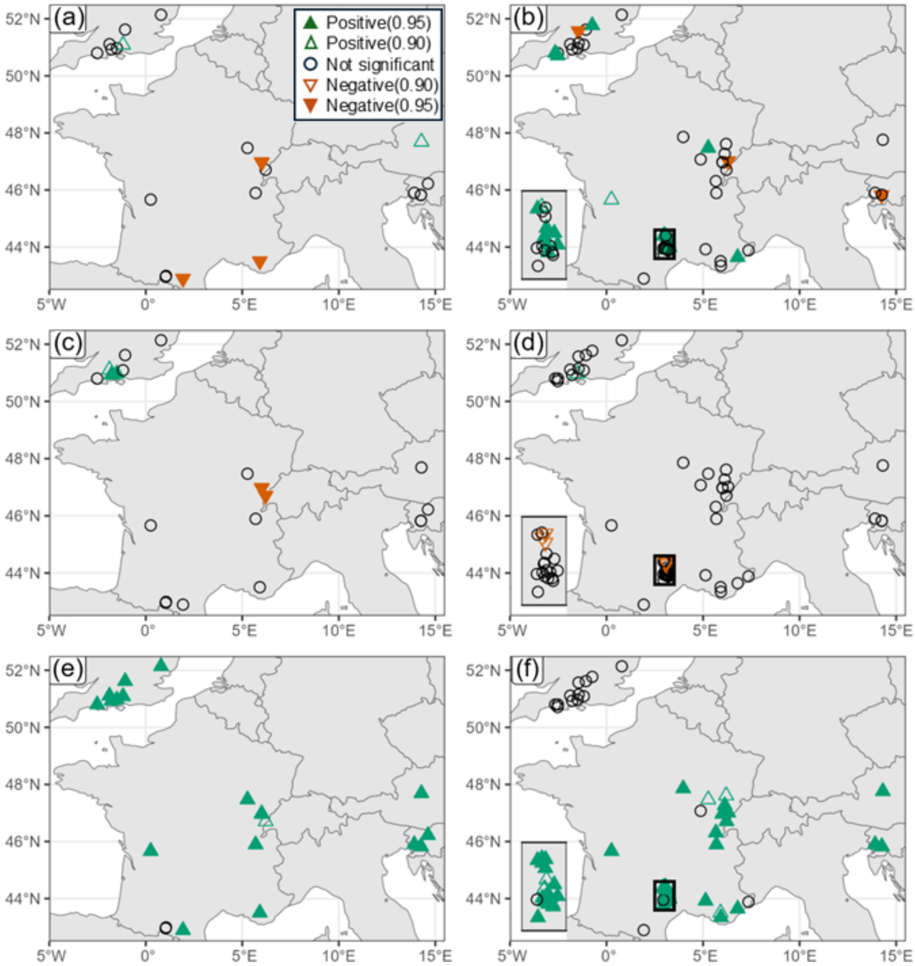

Figure 2. Trends in discharge **(a, b)**, precipitation **(c, d)**, and temperature **(e, f)** over the 40-year (1982–2021, left) and the 20-year (2002–2021, right) periods respectively. Orange symbols indicate negative trends while green symbols indicate positive trends.

show a wide range of negative and positive values. There are no major differences in the sign or overall trends between the two periods. However, the magnitude of changes is much greater in the shorter period, a pattern observed in all seasons except for fall, where the 40-year period also shows high variability. In winter, most changes are not significant. In contrast, spring and summer seasons display a clear increase in significant discharge changes over the last 20 years, with the majority of these changes being significantly positive. Precipitation trends, however, show no clear pattern, although spring appears slightly wetter and summer drier on a continental scale. In these two seasons, differences between the springs are minor compared to winter. The most pronounced trend is a decrease in precipitation during fall, often combined with a dominant decrease in discharge. This trend is evident in both periods, though slightly amplified in the last 20 years. Therefore, it can be concluded that fall is the only season with a clear long-term connection between precipitation and discharge, indicating a high sensitivity of spring discharge changes to changes in precipitation.

3.3 Low and high flow conditions

To analyse changes in low and high extremes, a trend analysis was conducted on the 0.1 and 0.9 quantiles of spring discharge. In Fig. 4, trend changes are expressed by Sen's slopes in $m^3\,yr^{-1}$, with changes in high flow (Q0.9) and low flow (Q0.1) conditions plotted on the y axis and x axis respectively. Since the springs differ in discharge dynamics, which influence mean annual discharge (see Table 1), directly comparing relative changes in annual high and low flow discharge and total annual discharge is challenging. For this reason, normalized values are used in Fig. 4. The figure is divided into four quadrants, where the upper-right and lower-left represent a uniform shift in discharge to a higher or lower stage respectively. The other two quadrants represent conditions where the fluctuation in discharge either increases (upper-left) or decreases (lower-right).

Comparing the trend development of extremes between the two different periods provides valuable insights into recharge patterns. For springs with significant changes in an-

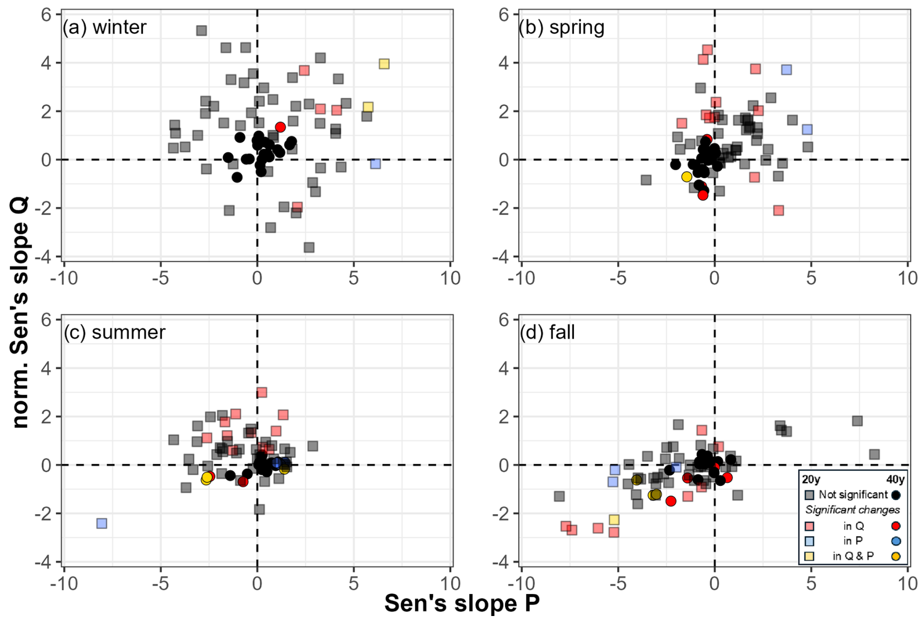

Figure 3. Comparison of changes in precipitation and discharge trends for **(a)** winter, **(b)** spring, **(c)** summer, and **(d)** fall. Each point represents a karst spring, with colours indicating trends: red for significant changes in discharge (Q), blue for significant changes in precipitation (P), yellow for significant changes in both Q and P, and black for insignificant changes. Circles denote springs with trends over the 40-year period, while squares represent 20-year trends.

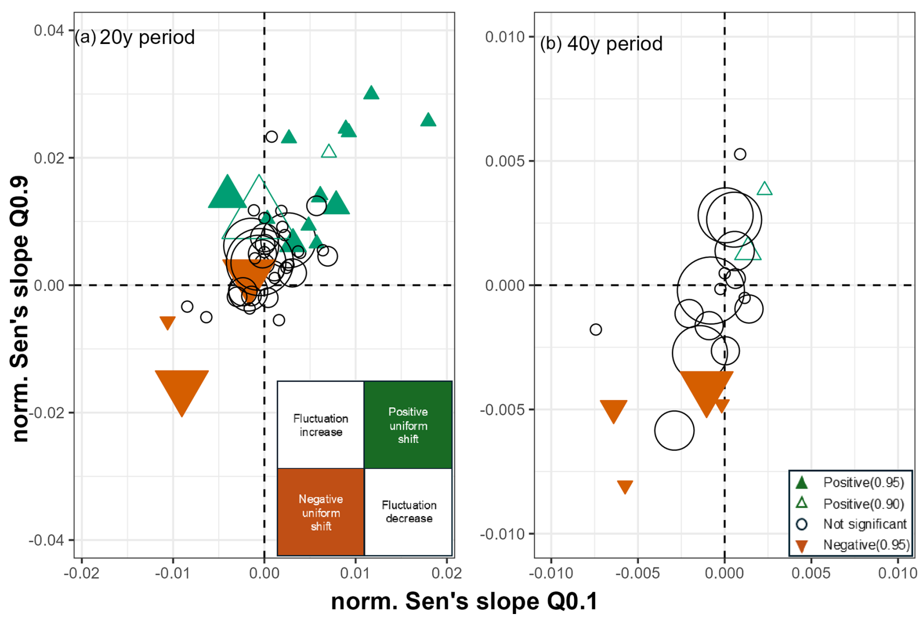

Figure 4. Distribution of high flow (Q0.9) and low flow (Q0.1) trends for **(a)** the 20-year period and **(b)** the 40-year period. Shape and colour of the symbols refer to the monthly discharge trends presented in Fig. 2a and b. The size of the symbols represents the size of the spring expressed by Q_{mean}.

nual spring discharge over the last 40 years, the entire spring discharge shifts uniformly either to a lower or higher stage, depending on the direction of the global trend. All springs with negative trends in annual discharge are located in the bottom-left quadrant, which is associated with decreases in both low and high flow. Most other springs without a significant trend also follow this pattern and can be found either in the top-right or bottom-left quadrants. Only two springs deviate from this general pattern, showing a slightly negative Sen's slope for high flow discharge alongside a positive low flow discharge. For the 20-year period, several springs deviate from this distribution including three with significant changes in annual discharge. All of these springs are located in the top-left quadrant, where opposing trends in low and high flow discharge are observed. In two cases, the increase in high flow discharge leads to a significant increase in annual spring discharge, while one spring shows a significant decrease in annual spring discharge despite the increase in high flow discharge. All other springs, located in the lower-left or upper-right quadrant, follow the pattern observed in the 40-year period. Springs with significant increasing discharge trends are found exclusively in the upper-right quadrant, while those with decreasing trends are located solely in the lower-left quadrant.

3.4 Sensitivity of different karst systems to changing climatic conditions

Due to the significant differences in hydraulic properties, karst systems respond differently to input signals. To characterize the springs based on their hydraulic properties, a simplified classification using BFI and memory index is presented in Fig. 5. In this representation, each spring is depicted as a point in the coordinate system, where each axis corresponds to one of the indices starting from zero at the origin and increasing along the respective axis. The coordinate system allows for a simplified classification of the systems, with two endmembers located in the lower-left and the top-right corners. The lower-left corner represents systems with a low fraction of slow flow components and low storativity, which are typical of mature karst systems. In contrast, the top-right corner represents fissured system with high storage capacity and a high degree of diffuse recharge.

Figure 5 illustrates the diversity of European karst systems, ranging from fast-responding systems with memory values of only a few days and a low fraction of slow flow components, to fractured systems, which are characterized by a high fraction of slow flow components and high inertia. Despite this variability, all springs generally follow one trend with some deviations at the extremes of the spectrum. This general trend forms a vertical line from the lower-left to the top-right corner. Among the fissured systems, in the range of BFI > 0.85, two springs deviate from this general trend by exhibiting higher memory values. A second deviation is observed among the mature karst systems, where several springs show an increased fraction of slow flow components. Despite the clear differences in hydraulic properties, significantly positive and negative trends cover the entire spectrum of springs. However, springs with extremely high values of both BFI (> 0.8) and memory (> 90 d) tend to show increasing or stable discharge trends. Based on these results from the continental discharge dataset, it is not possible to directly link hydraulic properties, deduced form discharge data, to climate resilience.

4 Discussion

Summarizing the continental trends, air temperature trends are the most pronounced hydroclimatic changes observed during both analysed periods. Over the past 40 years, air temperature has increased consistently across the recharge areas of European karst springs. However, over the last 20 years, this trend has slowed in some regions, particularly in England. Significant precipitation trends are scarce for both periods. Over the 40-year period, significant precipitation trends are observed only locally, and their significance and spatial occurrence further decrease over the last 20 years.

When considering only long-term hydroclimatic trends, it becomes challenging to fully attribute changes in discharge from karst areas to hydroclimatic variations. This may be due to additional factors such as groundwater abstraction, land cover changes, and shifts in agricultural practices, none of which are accounted for in this analysis. Moreover, trends in spring discharge are influenced not only by long-term hydroclimatic changes but also by short-term (e.g. seasonal) processes, such as variations in groundwater recharge and storage dynamics. To better understand these changes, it is necessary to explore potential process changes within specific regional contexts, which follows a comparison of general discharge trends with regional variations in river discharge.

4.1 Comparative analysis with surface water

Due to the relatively high abundance of hydrometric stations, numerous trend analyses of river discharge have been conducted both on continental and local scales. These studies are valuable for comparing with trends observed in karst areas. On a European scale, river discharge trends exhibit clear regional patterns closely connected to climatic drivers in recent decades. The increase in (extreme) precipitation results in positive trends in river discharge at the majority of hydrometric stations in north-western Europe (Harrigan et al., 2018; Blöschl et al., 2019) even though central and southern England, as well as northern France, show only a few significant trends (Vicente-Serrano et al., 2019). Conversely, in southern Europe, regional river discharge trends are spatially negative as a consequence of increasing temperatures and a decline in precipitation (Blöschl et al., 2019; Vicente-Serrano et al., 2019). One exception is the Pyrenees Mountains, where – contrary to karst springs – streamflow trends based on 67 river gauging stations covering both the north and south sides are largely insignificant for the period between 1980 and 2013 (Clavera-Gispert et al., 2023). Despite the limited spatial coverage of long-term karst spring data, the results in Fig. 2 demonstrate the ability to detect the long-term impact of changing hydroclimatic conditions on karst water resources at a continental scale. The general patterns observed in spring discharge align with trends in surface runoff.

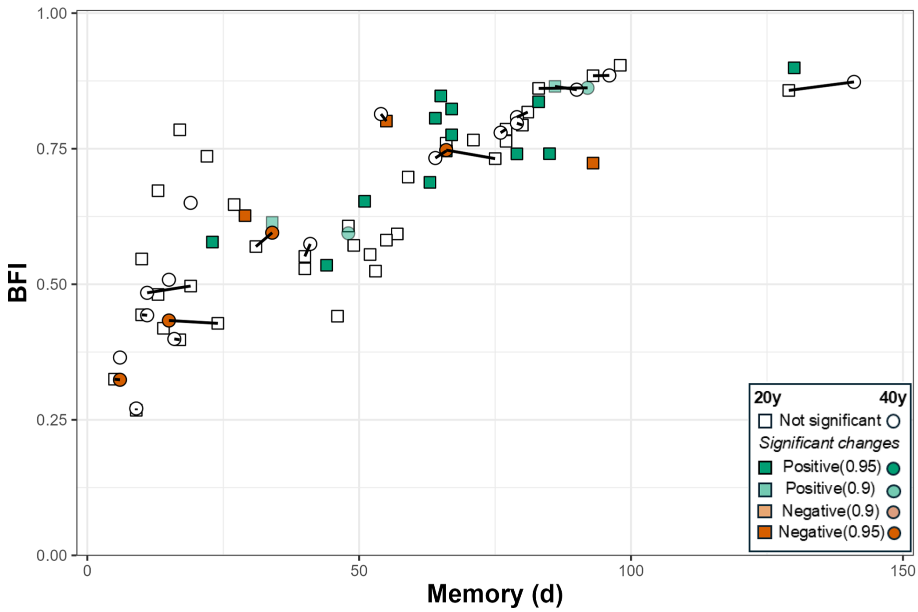

Figure 5. Classification of karst systems based on base flow index (BFI) and memory value. Squares represent 20-year trends, while circles represent 40-year trends. The colour indicates significant changes: green for positive trends and orange for negative trends, with different shades corresponding to confidence levels (0.95 and 0.9). White symbols indicate non-significant trends. Black lines connect symbols representing the same spring across the two time periods, illustrating temporal changes in BFI and memory.

High flow conditions in the karst system, described by the 90th percentile, follow the general trends in monthly discharge over the long period (Fig. 4), consistent with findings from European river systems. These regional flood trends show distinct patterns. Increasing trends in flood magnitude and frequency are dominant around the Atlantic (Mangini et al., 2018), with positive trends in high flow indices for all seasons except spring between 1985 and 2014 in the UK (Harrigan et al., 2018). In south-east France, river trends are mostly negative and decreasing flood magnitudes are evident in the southern part of the Alps (Mangini et al., 2018). In the Mediterranean, flood frequency decreases while flood magnitude trends increase for moderate (95th percentile) and severe (99th percentile) floods (Mangini et al., 2018; Tramblay et al., 2019). Additionally, changes can also be detected in the flood characteristics, most prominently in a considerable increase in medium to large flash flood occurrence in Europe in the 21st century compared to the 1980s (Owen et al., 2018), though major floods (25- to 100-year return period) show an overall, yet insignificant, increase (Hodgkins et al., 2017).

The consistency between European flood and karst flow trends indicates that groundwater recharge in karst areas aligns with surface runoff trends at a catchment scale. This suggests that global changes in hydroclimatic variables impact both runoff and infiltration components of the water cycle. The concentrated infiltration typical of karstic systems likely amplifies these trends, while other aquifer types may experience more buffering effects due to their greater inertia.

However, the evolution of high and low flow trends in karst areas over the different periods indicates potential process changes in recent decades (Fig. 4). Over the 40-year period, most springs follow roughly a straight line from the lower-left to upper-right with springs showing overall decreasing discharge trends in the lower-left and those with increasing discharge trends in the upper-right. This indicates a uniform shift in discharge levels without significant changes in fluctuation patterns. In contrast, during the last 20 years more springs deviate from this behaviour, exhibiting positive high flow and negative low flow trends. This suggests an increase in annual fluctuations between high and low flow conditions. Some springs even have significant overall discharge trends, driven by an increase in high flow events for rising trends and baseflow reduction but more extreme events for declining trends. This is a strong indication for changes in the partitioning of concentrated and diffuse recharge, suggesting alterations in precipitation patterns. However, considering the results from the analysis of indices closely related to the maturity or degree of karstification (memory effect and BFI; Fig. 5), it becomes clear that it is not only systems with a high fast flow component fraction that are impacted. Hence, the sensitivity of karst aquifers to climate change is not solely controlled by their degree of karstification. Instead, the effects linked to hydraulic properties appear to be masked by the regional influence of hydroclimatic changes occurring on different timescales.

4.2 Hydroclimate-induced changes in karst water resources

Changes on a regional scale depend not only on the climate zone but also on specific regional conditions. Even though a detailed local-scale analysis is beyond the scope of this study, evidence supporting some of the described discharge trends can be given. According to the results, fall is the season with the highest sensitivity of spring discharge to changes in precipitation (Fig. 3). A plausible explanation involves the combination of two phenomena with significant consequences: (i) the depletion of the aquifers in fall due to the warmer spring/summer temperatures and (ii) a lower recharge at the start of the hydrological cycle. This can be discussed at a smaller scale, for specific regions with consistent spatial trends.

Over the last 40 years, discharge has decreased in the Springs Lison and Verneau, both situated in the same part of the Jura Mountains and characterized by long-term discharge records (40 years). Looking at the general trends in the area (Fig. 6), temperature, and consequently evapotranspiration, has increased across all seasons over the last 40 years. This, combined with significantly decreasing fall precipitation, contributes to lower discharge in fall. In the entire region, the distribution of precipitation shifted, with more precipitation in winter and spring but less during the other two seasons. Over 40 years, the partially significant decrease in fall precipitation might explain the local precipitation decline in the area (Fig. 2d).

During the past 20 years, precipitation in spring and, particularly, winter has increased significantly, which might explain the absence of consistent negative discharge trends during this period. In addition to the increase in winter precipitation, winter air temperature has also risen, accelerating over the last 20 years. In mountainous regions, this likely results in reduced snow contribution, a pattern supported by earlier studies reporting a significant decrease in snow precipitation in the northern part of the Jura Mountains (Charlier et al., 2022). In summary, long-term changes in the Jura Mountains are mainly related to rising temperature, affecting snow contribution during cold seasons and increasing evapotranspiration during warm seasons. Both effects have been highlighted in previous studies of karst systems in temperate climates (Fan et al., 2023) and mountainous regions with Mediterranean climates (Lorenzi et al., 2022). However, in the case of Jura Mountains, these changes do not result in overall regional-wide decreasing discharge. A likely explanation is that increased evapotranspiration is offset by higher precipitation in cold seasons over the past 20 years, a process previously discussed for south-western England (Brenner et al., 2018).

The Grand Causses region is of particular interest due to its location along a climate zone boundary. Previous studies have highlighted that such areas, especially those affected by changes in snow contributions, are susceptible to variations in river discharge (Berghuijs et al., 2014) and groundwater level variability (Nygren et al., 2020, 2021). The climate boundary in the Grand Causses region is shaped by elevation differences, dividing the lower parts with a Mediterranean climate from the parts with higher elevation (temperate climate). Based on the results in Fig. 2b, several springs in the region show positive discharge trends over the past 20 years. However, precipitation increases mainly in spring and has a clear negative trend in fall and winter for both climate zones (Fig. 7), linked to a lower occurrence of Mediterranean storm events – which historically occurred in fall – over the last decades. The most significant discharge changes are observed in summer, all of which are positive. Similar to the Jura Mountains, air temperatures have increased across all seasons, most pronounced in winter. Despite the decrease in winter precipitation, spring discharge shows an increase, although not statistically significant. This regional discharge trend indicates increases in all seasons except fall. This aligns with reduced precipitation and, consequently, decreased recharge during fall. One potential explanation for the overall discharge increase could be a substantial reduction in snow contribution. This, combined with higher precipitation in spring, likely leads to the saturation of the system. Despite elevated temperatures in the warmer seasons, the increased recharge supports greater discharge levels, which persist until fall.

4.3 Additional forcings impacting karst water resources

Building on the analysis of the Jura Mountains and Grands Causses region, it can be concluded that, in the absence of significant precipitation changes, temperature is the primary driver of climate change-related trends in European karst discharge. Anthropogenic warming is closely linked to increased evapotranspiration, which affects the entire hydrological cycle and is closely connected to the occurrence of meteorological (e.g. Hänsel et al., 2019; Philip et al., 2020), soil moisture (e.g. Samaniego et al., 2018; Philip et al., 2020), and groundwater drought (e.g. Bloomfield et al., 2019).

Changes in land use or land cover also play a critical role in influencing evapotranspiration. Several studies have highlighted the influence of land use changes on river discharge trends (e.g. Vicente-Serrano et al., 2019) and extreme events, especially the spatial and temporal occurrence and severity of droughts (e.g. Brunner and Stahl, 2023). Even short-term changes such as crop rotations in agricultural areas directly affect groundwater storage (e.g. Dakhlalla et al., 2016). On a global scale, almost 5 % of karst regions experienced land use or land cover changes between 1992 and 2020, predominantly due to agricultural reclamation or reforestation (Zhang et al., 2023). However, analysing the impact of these changes on a larger scale is challenging due to the lack of fundamental

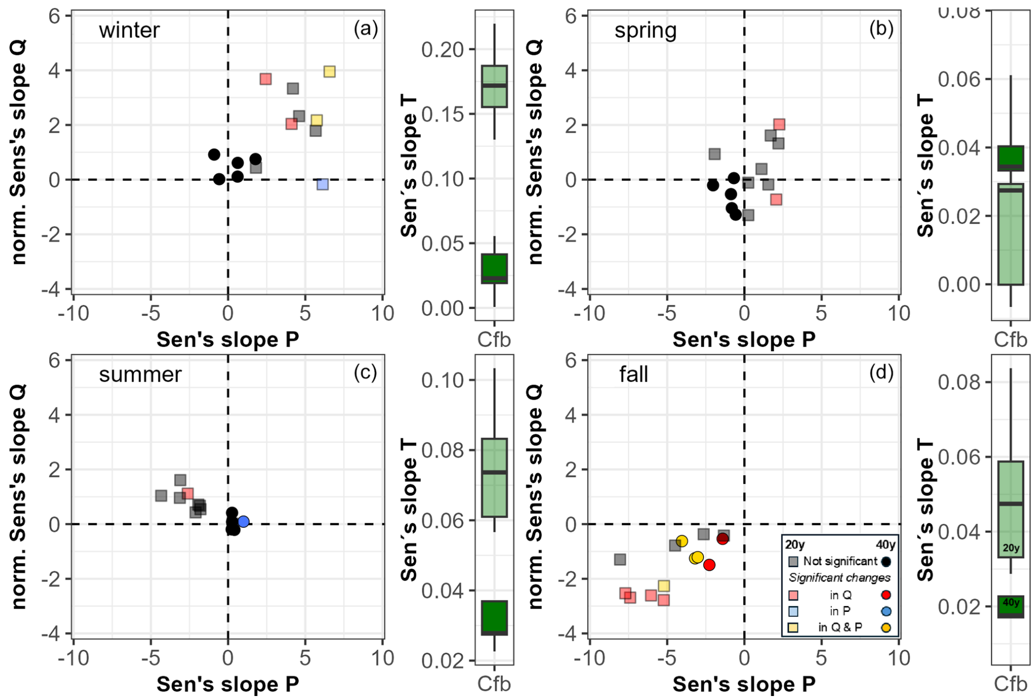

Figure 6. Comparison of changes in precipitation and discharge trends for **(a)** winter, **(b)** spring, **(c)** summer, and **(d)** fall in combination with temperature (boxplot) for all springs located in the Jura Mountains (France, Cfb – Temperate oceanic climate zone). Each point represents a karst spring, with colours indicating trends: red for significant changes in discharge (Q), blue for significant changes in precipitation (P), yellow for significant changes in both Q and P, and black for non-significant changes. Circles denote springs with trends over the 40-year period, while squares represent 20-year trends. The line in the boxplot represents the median.

research on percolation and recharge processes in karst areas, particularly those covered by forest (Vilhar et al., 2022).

Possible explanations for the increase in discharge or moderated downward trends – not only in the Grands Causses region – can also be found in the dependence of spring discharge on large-scale atmospheric circulations, as observed in Italian karst areas (e.g. Fiorillo et al., 2021). Abrupt changes or even disruptions in system behaviour over the past decades are evident in other components of the hydrological cycle, driven by fluctuations in large-scale atmospheric circulations. These circulations impact hydroclimatic variables such as wind speed, temperature, and precipitation across Europe (e.g. Ionita et al., 2022; Deng et al., 2022). For European river basins, the 1980s marked the first time that periodic changes in river discharge became closely linked to large-scale atmospheric circulations, such as the North Atlantic Oscillation (Lorenzo-Lacruz et al., 2022). This transient connection between periodic fluctuations in European river discharge and large-scale atmospheric circulations is evident on both continental (e.g. Lorenzo-Lacruz et al., 2022) and regional scales (e.g. Giuntoli et al., 2013; Boé and Habets, 2014). Furthermore, atmospheric circulations impact long-term groundwater level variability (e.g. Holman et al., 2011; Neves et al., 2019; Rust et al., 2018, 2019; Baulon et al., 2022). These periodic signals propagate through processes and, on average, account for 40 % to 55 % of groundwater level variability, playing a role as important as current climate conditions (Neves et al., 2019; Rust et al., 2019).

5 Conclusions

Observational data from European karst areas were analysed for two different periods. The first period (1982–2021) focuses on European springs with the longest available time series, while the second one covers the last 2 decades. The shorter period was selected to identify potential acceleration or moderation of trends on a regional scale. By analysing trends in observational hydroclimatic and hydrological variables over the last 20 years, this study provides continental insight into these changes and at the same time allowing for a larger number of karst springs representing diverse hydraulic properties, climates, and topographies.

The analysis of long-term discharge trends in European karst springs reveals that discharge does not change uniformly over time but follows distinct regional patterns. Over the past 40 years, trends in karst spring discharge have been influenced by changes in temperature and precipitation. Temperature increases played a pivotal role in explaining the observed trends, while precipitation changes alone, including seasonal variations, were insufficient to account for the de-

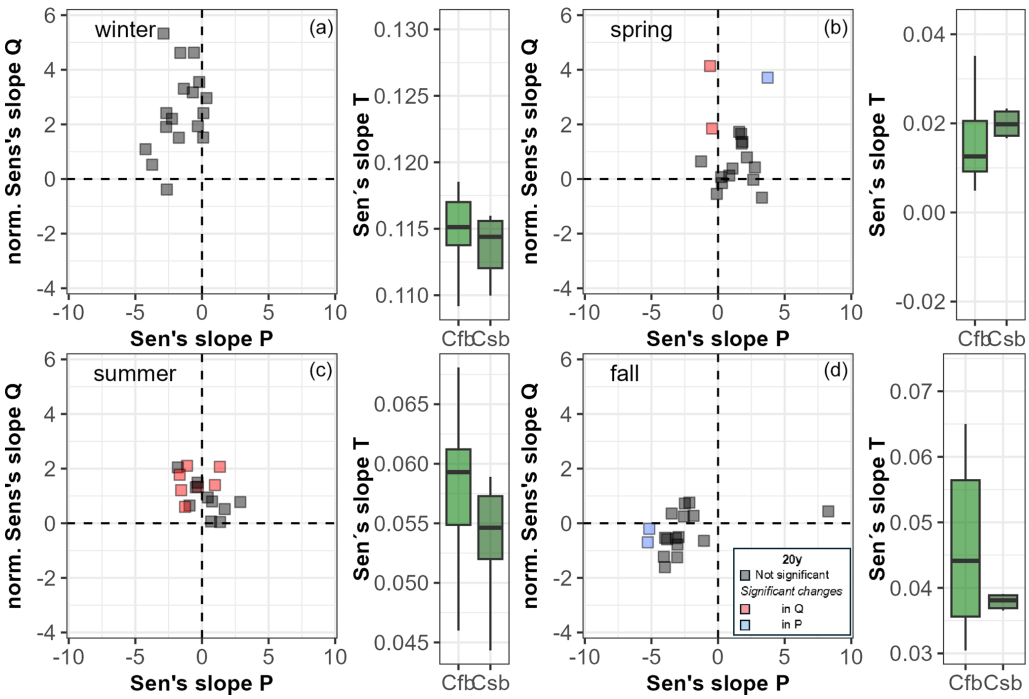

Figure 7. Comparison of changes in precipitation and discharge trends for **(a)** winter, **(b)** spring, **(c)** summer, and **(d)** fall in combination with temperature (boxplot) for all springs located in the Grand Causses region (France: Cfb – Temperate oceanic climate zone, Csb – Mediterranean climate zone). Each point represents a karst spring, with colours indicating trends: red for significant changes in discharge (Q), blue for significant changes in precipitation (P), and black for non-significant changes. The line in the boxplot represents the median.

tected discharge trends. The results suggest that increased evapotranspiration, changes in snow contribution, and shifts in seasonal precipitation distribution alter the flow regimes of karst systems, and, consequently, their impact on spring discharge varies depending on location.

Changes in discharge variability influence both low and high flow conditions. In general, long-term trends in discharge follow a uniform shift in flow conditions over the entire range of discharge. However, over the past 20 years, discharge fluctuations have become more pronounced, and several springs deviate from the uniform pattern observed over the longer term, notably due to an increase in high flow discharge. This suggests that recent climate or system changes may be altering recharge and storage processes, leading to increased variability in karst spring discharge.

Further, variability in karst spring discharge is closely linked to the hydrological properties of karst systems. Despite the common assumption that systems with higher baseflow components exhibit more stable discharge patterns, while those dominated by fast flow components show greater variability, this continental study does not establish a direct link between discharge-derived indices, describing storativity, and climate variability. On the contrary, the results suggest that long-term discharge trends are independent of the maturity or degree of karstification as characterized by these indices.

This may, in part, reflect the inherent simplifications in the analysis of observational data, which do not fully capture the complexity of groundwater recharge and flow processes in karst areas. These dynamics can be better addressed through process-based groundwater recharge model approaches. However, the results presented here have a practical implication for modelling discharge in karst areas. Most time series are relatively short, which increases the risk of basing analyses on periods influenced by changing climate conditions without accounting for associated shifts. Moreover, developing numerical models and validating them using trend-affected time series – without considering the underlying drivers or evolving processes – risks producing misleading future predictions of spring discharge by assuming continuous linear trends. Utilizing process-based groundwater recharge models to analyse discharge changes in karst areas may minimize the risk and help overcome challenges associated with model validation.

Code availability. The R code used to process and analyze the spring discharge and climate data is archived and openly available on Zenodo at https://doi.org/10.5281/zenodo.15870548 (Giese, 2025). All external R packages required to run the analysis are explicitly listed in the article to ensure transparency and reproducibility.

Data availability. Spring discharge data used in this study were obtained from the World Karst Spring Hydrograph dataset (WOKAS) (Olarinoye et al., 2020) and directly from the French national hydrological database Hydroportail (https://www.hydro.eaufrance.fr/, Eaufrance, 2025). The R code to download the WOKAS datasets directly from the source mentioned above is available at https://github.com/KarstHub/WoKaS (last access: 11 August 2023).

Precipitation and temperature data were obtained from the daily gridded observational dataset for Europe (E-OBS): https://surfobs.climate.copernicus.eu/.

Author contributions. Conceptualization: MG, JBC, YC, AH, formal analysis: MG, funding acquisition: MG, JBC, YC, methodology: MG, JBC, YC, AH, software: MG, visualization: MG, writing – original draft preparation: MG, JBC, YC, AH, writing – review and editing: MG, JBC, YC, AH.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Acknowledgements. The Authors would like to thank the French Ministry of Europe and Foreign Affairs for its financial support within the MOPGA Fellowship Program.

Financial support. This research has been supported by Campus France, and Markus Giese was financed through the MOPGA Fellowship Program (grant no. 127244W).

Review statement. This paper was edited by Alberto Guadagnini and reviewed by two anonymous referees.

References

Bailly-Comte, V., Ladouche, B., Charlier, J.-B., Hakoun, V., and Maréchal, J.-C.: XLKarst, an Excel tool for time series analysis, spring recession curve analysis and classification of karst aquifers, Hydrogeol. J., 31, 2401–2415, https://doi.org/10.1007/s10040-023-02710-w, 2023.

Bakalowicz, M.: Karst groundwater: a challenge for new resources, Hydrogeol. J., 13, 148–160, https://doi.org/10.1007/s10040-004-0402-9, 2005.

Barthel, R., Stangefelt, M., Giese, M., Nygren, M., Seftigen, K., and Chen, D.: Current understanding of groundwater recharge and groundwater drought in Sweden compared to countries with similar climate, Geogr. Ann. A, 103, 323–345, https://doi.org/10.1080/04353676.2021.1969130, 2021.

Baulon, D., Massei, N., Bessiere, H., Fournier, M., and Bault, V.: Influence of low-frequency variability on groundwater level trends, J. Hydrol., 606, 127436, https://doi.org/10.1016/j.jhydrol.2022.127436, 2022.

Berghuijs, W. R., Woods, R. A., and Hrochowitz, M.: A precipitation shift from snow towards rain leads to a decrease in streamflow, Nat. Clim. Change, 4, 583–586, https://doi.org/10.1038/NCLIMATE2246, 2014.

Binet, S., Probst, J.-L., Batiot, C., Seidel, J. L., Emblanch, C., Peyraube, N., Charlier, J.-B., Bakalowicz, M., and Probst, A.: Global warming and acid atmospheric deposition impacts on carbonate dissolution and CO_2 fluxes in French karst hydrosystems: Evidence from hydrochemical monitoring in recent decades, Geochim. Cosmochim. Ac., 270, 184–200, https://doi.org/10.1016/j.gca.2019.11.021, 2020.

Binet, S., Charlier, J.-B., Jozja, N., Défarge, C., and Moquet, J. S.: Evidence of long term biogeochemical interactions in carbonate weathering: The role of planktonic microorganisms and riverine bivalves in a large fluviokarst system, Sci. Total Environ., 842, 156823, https://doi.org/10.1016/j.scitotenv.2022.156823, 2022.

Bloomfield, J. P., Marchant, B. P., and McKenzie, A. A.: Changes in groundwater drought associated with anthropogenic warming, Hydrol. Earth Syst. Sci., 23, 1393–1408, https://doi.org/10.5194/hess-23-1393-2019, 2019.

Blöschl, G., Hall, J., Viglione, A., Perdigao, R. A. P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T., Bilibashi, A., Bohac, M., Bonacci, O., Borga, M., Canjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gul, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnova, 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., Salinas, J. L., Sauquet, E., Sraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., and Zivkovic, N.: Changing climate both increases and decreases European river floods, Nature, 573, 108–111, https://doi.org/10.1038/s41586-019-1495-6, 2019.

Boé, J. and Habets, F.: Multi-decadal river flow variations in France, Hydrol. Earth Syst. Sci., 18, 691–708, https://doi.org/10.5194/hess-18-691-2014, 2014.

Brenner, S., Coxon, G., Howden, N. J. K., Freer, J., and Hartmann, A.: Process-based modelling to evaluate simulated groundwater levels and frequencies in a Chalk catchment in southwestern England, Nat. Hazards Earth Syst. Sci., 18, 445–461, https://doi.org/10.5194/nhess-18-445-2018, 2018.

Brunner, M. I. and Stahl, K.: Temporal hydrological drought clustering varies with climate and land-surface processes, Environ. Res. Lett., 18, 034011, https://doi.org/10.1088/1748-9326/acb8ca, 2023.

Charlier, J.-B., Ladouche, B., and Maréchal, J.-C.: Identyfying the impact of climate and anthropic pressure on karst aquifers using wavelet analysis, J. Hydrol., 523, 610–623, https://doi.org/10.1007/s10040-016-1519-3, 2015.

Charlier, J.-B., Tourenne, D., Hévin, G., Desprats, J.-F.: NUTRI-Karst – Réponses des agro-hydro-systèmes du massif du Jura face au changement climatique et aux activités anthropiques, BRGM/RP-72229-FR report, 238 pp., http://infoterre.brgm.fr/

rapports/RP-72229-FR.pdf (last access: June 2024), 2022 (in French).

Chen, Z., Auler, A. S., Bakalowicz, M., Drew, D., Griger, F., Hartmann, J., Jiang, G., Mossdorf, N., Richts, A., Stevanovic, Z., Veni, G., and Goldscheider, N.: The world karst aquifer mapping project: concept, mapping prodecure and map of Europe, Hydrogeol. J., 25, 771–785, https://doi.org/10.1007/s10040-016-1519-3, 2017.

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, 127006, https://doi.org/10.1016/j.jhydrol.2021.127006, 2021.

Clavera-Gispert, R., Quintana-Seguí, P., Palazn, L., Zabaleta, A., Cenobio, O., Barella-Ortiz, A., and Beguería, S.: Streamflow trends of the Pyrenees using observations and multi-model approach (1980–2013), Journal of Hydrology: Regional Studies, 46, 101322, https://doi.org/10.1016/j.ejrh.2023.101322, 2023.

Cornes, R., van der Schrier, G., van den Besselaar, E. J. M., and Jones, P. D.: 2018: An ensemble version of the E-OBS temperature and precipitation datasets, J. Geophys. Res.-Atmos., 123, 9391–9409, https://doi.org/10.1029/2017JD028200, 2018.

Dakhlalla, A. O., Parajuli, P. B., Ouyang, Y., and Schmitz, D.W.: Evaluating the impacts of crop rotations on groundwater storage and recharge in an agricultural watershed, Agr. Water Manage., 163, 332–343, https://doi.org/10.1016/j.agwat.2015.10.001, 2016.

Deng, K.-Q., Azorin-Molina, C., Yang, S., Hu, C.-D., Zhang, G.-F., Molina, L., Vicente-Serrano, S., and Chen, D.: Shifting of summertime weather extremes in Western Europe during 2012–2020, Advances in Climate Change Research, 13, 218–227, https://doi.org/10.1016/j.accre.2022.01.008, 2022.

De Vita, P., Allocca, V., Manna, F., and Fabbrocino, S.: Coupled decadal variability of the North Atlantic Oscillation, regional rainfall and karst spring discharges in the Campania region (southern Italy), Hydrol. Earth Syst. Sci., 16, 1389–1399, https://doi.org/10.5194/hess-16-1389-2012, 2012.

Dubois, E., Doummar, J., Pistre, S., and Larocque, M.: Calibration of a lumped karst system model and application to the Qachqouch karst spring (Lebanon) under climate change conditions, Hydrol. Earth Syst. Sci., 24, 4275–4290, 2020.

Eaufrance: Hydroportail, Eaufrance [data set], https://www.hydro.eaufrance.fr/, last access: 25 June 2025.

Eckhardt, K.: How to construct recursive digital filters for baseflow separation, Hydrol. Process., 19, 507–515, https://doi.org/10.1002/hyp.5675, 2005.

Fan, X., Goeppert, N., and Goldscheider, N.: Quantifiying 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. and Doglioni, A.: The relation between karst spring discharge and rainfall by cross-correlation analysis (Campania, southern Italy), Hydrogeol. J., 18, 1881–1895, https://doi.org/10.1007/s10040-010-0666-1, 2010.

Fiorillo, F. and Guadango, F. M.: Long karst spring discharge time series and droughts occurrence in Southern Italy, Environ. Earth. Sci., 65, 2273–2283, https://doi.org/10.1007/s12665-011-1495-9, 2012.

Fiorillo, F., Petitta, M., Preziosi, E., Rusi, S., Esposito, L., and Tallini, M.: Long-term trend and fluctuations of karst spring discharge in a Mediterranean area (central-southern Italy), Environ. Earth. Sci., 74, 153–172, https://doi.org/10.1007/s12665-014-3946-6, 2015.

Fiorillo, F., Leonel, 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.: Karst Hydrogeology and Geomorphology, John Wiley & Sons Ltd, Chichester, https://doi.org/10.1002/9781118684986, 2007.

Giese, M.: Trends in long-term hydrological data from European karst areas: insights for groundwater recharge evaluation, Zenodo [code], https://doi.org/10.5281/zenodo.15870548, 2025.

Giuntoli, I., Renard, B., Vidal, J.-P., and Bard, A.: Low flows in France and their relationship to large-scale climate indices, J. Hydrol., 482, 105–118, 2013.

Goldscheider, N., Chen, Z., Auler, A. S., Bakalowicz, M., Broda, S., Drew, D., Hartmann, J., Jiang, G., Moosdorf, N., Stevanovic, Z., and Veni, G.: Global distribution of carbonate rocks and karst water resources, Hydrogeol. J., 28, 1661–1677, 2020.

Haas, J. C. and Birk, S.: Trends in Austrian groundwater – Climate or human impact, Journal of Hydrology: Regional Studies, 22, 100597, https://doi.org/10.1016/j.ejrh.2019.100597, 2019.

Hamed, K. H. and Rao, R.: A modified Mann-Kendall trend test for autocorrelated data, J. Hydrol., 204, 182–196, 1998.

Hänsel, S., Ustrnul, Z., Łupikasza, E., and Skalak, P.: Assessing seasonal drought variations and trends over Central Europe, Adv. Water Resour., 127, 53–75, https://doi.org/10.1016/j.advwatres.2019.03.005, 2019.

Harrigan, S., Hannaford, J., Muchan, K., and Marsh, T. J.: Designation and trend analysis of the updated UK Benchmark Network of river flow stations: The UKBN2 dataset, Hydrol. Res., 49, 552–567, https://doi.org/10.2166/nh.2017.058, 2018.

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., and Weiler, M.: Karst water resources in a changing world: Review of hydrological modeling approaches, 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, P. Natl. Acad. Sci. USA, 114, 2842–2847, https://doi.org/10.1073/pnas.1614941114, 2017.

Hodgkins, G. A., Whitfield, P. H., Burn, D. H., Hannaford, J., Renard, B., Stahl, K., Fleig, A. K., Madsen, H., Mediero, L., Korhonen, J., Murphy, C., and Wilson, D.: Climate-driven variability in the occurrence of major floods across North America and Europe, J. Hydrol., 552, 704–717, https://doi.org/10.1016/j.jhydrol.2017.07.027, 2017.

Holman, I. P., Rivas-Casado, M., Bloomfield, J. P., and Gurdak, J. J.: Identifying non-stationary groundwater level response to North Atlantic ocean-atmosphere teleconnection patterns using wavelet coherence, Hydrogeol. J., 19, 1269–1278, https://doi.org/10.1007/s10040-011-0755-9, 2011.

Ionita, M., Nagavciuc, V., Scholz, P., and Dima, M.: Long-term drought intensification over Europe driven by the weakening trend of the Atlantic Meridional Overturning Circulation, Journal of Hydrology: Regional Studies, 42, 101176, https://doi.org/10.1016/j.ejrh.2022.101176, 2022.

IPCC: Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, ISBN 978-1009157889, 2021.

Jódar, J., González-Ramón, A., Martos-Rosillo, S., Heredia, J., Herrera, C., Urrutia, J., Caballero, Y., Zabaleta, A., Antigüedad, I., Custodio, E., and Lambán, L. J.: Snowmelt as a determinant factor in the hydrogeological behaviour of high mountain karst aquifers: The Garcés karst system, Central Pyrenees (Spain), Sci. Total Environ., 748, 141363, https://doi.org/10.1016/j.scitotenv.2020.141363, 2020.

Kendall, M. G.: Rank Correlation Methods, Griffin, ISBN 0-85264-199-0, 1948.

Kovacic, G., Petric, M., and Ravbar, N.: Evaluation and quantification of the effects of climate and vegetation cover change on karst water sources: case studies of two springs in south-western Slovenia, Water-Sui., 12, 3087, https://doi.org/10.3390/w12113087, 2020.

Ladson, A. R., Brown, R., Neal, B., and Nathan, R.: A standard approach to baseflow separation using the Lyne and Hollick filter, Australian Journal of Water Resources, 17, 173–180, 2013.

Lanini, S. and Caballero, Y.: ESPERE, a tool for multi-method aquifer recharge estimation: What' s new with version 2?, Groundwater, 59, 5–6, https://doi.org/10.1111/gwat.13049, 2021.

Larocque, M., Mangin, A., Razack, M., and Banton, O.: Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France), J. Hydrol., 205, 217–231, https://doi.org/10.1016/S0022-1694(97)00155-8, 1998.

Leone, G., Pagnozzi, M., Catani, V., Ventafridda, G., Esposito, L., and Fiorillo, F.: A hundred years of Caposele spring discharge measurements: trends and statistics for understanding water resource availability under climate change, Stochastical Environmental Research and Risk Assessment, 35, 345–370, https://doi.org/10.1007/s00477-020-01908-8, 2021.

Lorenzi, V., Sbarbati, C., Benzato, F., Lacchini, A., and Petitta, M.: Recharge assessment of the Gran Sasso aquifer (Central Italy): Time-variable infiltration and influence of snow cover extension, Journal of Hydrology: Regional Studies, 41, 101090, https://doi.org/10.1016/j.ejrh.2022.101090, 2022.

Lorenzo-Lacruz, J., Moran-Tejeda, E., Vicente-Serrano, S. M., Hannaford, J., Garcia, C., Pena-Angulo, D., and Murphy, C.: Streamflow frequency changes across western Europe and interactions with North Atlantic atmospheric circulation patterns, Global Planet. Change, 212, 103797, https://doi.org/10.1016/j.gloplacha.2022.103797, 2022.

Lyne, V. and Hollick, M.: Stochastic time-variable rainfall-runoff modelling, Hydrology and Water Resources Symposium. Institution of Engineers Australia, National Conference, January 1979, Perth, Western Australia, 89–93, 1979.

Maillet, E. T.: Essais d'hydraulique souterraine et fluviale, Herman et Cle, Paris, 1905.

Mangin, A.: Contribution à l'étude hydrodynamique de aquifères karstiques, PhD thesis, Université de Dijon, France, 1975.

Mangin, A.: Pour une meilleure connaissance des systèmes hydrologiques à partir des analyses corrélatoire et spectrale, J. Hydrol., 67, 25–43, https://doi.org/10.1016/0022-1694(84)90230-0, 1984.

Mangini, W., Viglione, V., Hall, J., Hundecha, Y., Ceola, S., Montanari, A., Rogger, M., Salina, J. L., Borzi, I., and Paraika, J.: Detection of trends in magnitude and frequency of flood peaks across Europe, Hydrolog. Sci. J., 63, 493–512, https://doi.org/10.1080/02626667.2018.1444766, 2018.

Mann, H. B.: Nonparametric tests against trend, Econometrica, 13, 245–259, 1945.

Maréchal, J.-C., Ladouche, B., and Dörfliger, N.: Karst flash flooding in a Mediterranean karst, the example of Fontaine de Nîmes, Eng. Geol., 99, 138–146, https://doi.org/10.1016/j.enggeo.2007.11.013, 2008.

Martinsen, G., Bessiere, H., Caballero, Y., Koch, J., Collados-Lara, A. J., Mansour, M., Sallasmaa, O., Pulido-Velazquez, D., Hunter Williams, N., Jan Zaadnoordijk, W., and Stisen, S.: Developing a pan-European high-resolution groundwater recharge map – Combining satellite data and national survey data using machine learning, Sci. Total Environ., 822, 153464, https://doi.org/10.1016/j.scitotenv.2022.153464, 2022.

Moeck, C., Grech-Cumboa, N., Podgorski, J., Bretzler, A., Gurdak, J. J., Berg, M., and Schirmer, M.: A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships, Sci. Total Environ., 717, 137042, https://doi.org/10.1016/j.scitotenv.2020.137042, 2020.

Mohan, C., Western, A. W., Wei, Y., and Saft, M.: Predicting groundwater recharge for varying land cover and climate conditions – a global meta-study, Hydrol. Earth Syst. Sci., 22, 2689–2703, https://doi.org/10.5194/hess-22-2689-2018, 2018.

Neves, M. C., Jerez, S., and Trigo, R. M.: The response of piezometric levels in Portugal to NAO, EA, and SCAND climate patterns, J. Hydrol., 568, 1105–1117, https://doi.org/10.1016/j.jhydrol.2018.11.054, 2019.

Nygren, M., Giese, M., Kløve, B., Haaf, E., Rossi, P. M., and Barthel, R.: Changes in seasonality of groundwater level fluctuations in a temperate-cold climate transition zone, J. Hydrology X, 8, 100062, https://doi.org/10.1016/j.hydroa.2020.100062, 2020.

Nygren, M., Giese, M., and Barthel, R.: Recent trends in hydroclimate and groundwater levels in a region with seasonal frost cover, J. Hydrol., 602, 126732, https://doi.org/10.1016/j.jhydrol.2021.126732, 2021.

Olarinoye, T., Gleeson, T., Marx, V., Seeger, S., Adinehvand, R., Allocca, V., Andreo, B., Apaéstegui, J., Apolit, C., Arfib, B., Auler, A., Barberá, J. A., Batiot-Guilhe, C., Bechtel, T., Binet, S., Bittner, D., Blatnik, M., Bolger, T., Brunet, P., Charlier, J.-B., Chen, Z., Chiogna, G., Coxon, G., De Vita, P., Doummar, J., Epting, J., Fournier, M., Goldscheider, N., Gunn, J., Guo, F., Guyot, J. L., Howden, N., Huggenberger, P., Hunt, B., Jeannin, P. Y., Jiang, G., Jones, G., Jourde, H., Karmann, I., Koit, O., Kordilla, J., Labat, D., Ladouche, B., Liso, I. S., Liu, Z., Massei, N., Mazzilli, N., Mudarra, M., Parise, M., Pu, J., Ravbar, N., Sanchez, L. H., Santo, A., Sauter, M., Sivelle, V., Skoglund, R. Ø., Stevanovic, Z., Wood, C., Worthington, S., and Hartmann, A.: Global karst soring hydrograph dataset for research and management of the world' s fastest-flowing groundwater, Sci. Data, 7, 59, https://doi.org/10.1038/s41597-019-0346-5, 2020 (code available at: https://github.com/KarstHub/WoKaS, last access: 11 August 2023).

Owen, P. W., Roberts, G., Prigent, O., Markus, R., Tanguy, B., Bridgford, M., Katharina, B., Ciabatti, I., Gatter, L., Gilson, V., Kubat, J., Laanes, L., Simeonova, R., Critoph, H., and Annette, Z.: Flood Directive: progress in assessing risks, while planning and implementation need to improve, Special Report No. 25, Luxembourg, https://doi.org/10.2865/12240, 2018.

Padilla, A. and Pulido-Bosch, A.: Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis, J. Hydrol., 168, 73–89, https://doi.org/10.1016/0022-1694(94)02648-U, 1995.

Palacios-Cabrera, T., Valdes-Abellan, J., Jodar-Abellan, A., and Rodrigo-Cominod, J.: Land-use changes and precipitation cycles to understand hydrodynamic responses in semiarid Mediterranean karstic watersheds, Sci. Total Environ., 819, 153182, https://doi.org/10.1016/j.scitotenv.2022.153182, 2022.

Palmer, A. N.: Origin and morphology of limestone caves, Geol. Soc. Am. Bull., 103, 1–21, 1991.

Peña-Angulo, D., Reig-Gracia, F., Domínguez-Castro, F., Revuelto, J., Aguilar, E., van der Schrier, G., and Vicente-Serrano, S. M.: ECTACI: European climatology and trend atlas of climate indices (1979–2017), J. Geophys. Res.-Atmos., 125, e2020JD032798, https://doi.org/10.1029/2020JD032798, 2020.

Petitta, M., Benzato, F., Lorenzi, V., Matani, E., and Sbarbati, C.: Determining recharge distribution in fractured carbonate aquifers in central Italy using environmental isotopes: snowpack cover as an indicator for future availability of groundwater resources, Hydrogeol. J., 30, 1619–1636, https://doi.org/10.1007/s10040-022-02501-9, 2022.

Philip, S. Y., Kew, S. F., van der Wiel, K., Wanders, N., and van Oldenborgh, G. J.: Regional differentiation in climate change induced drought trends in the Netherlands, Environ. Res. Lett., 15, 094081, https://doi.org/10.1088/1748-9326/ab97ca, 2020.

Piggott, A. R., Moin, S., and Southam, C.: A revised approach to the UKIH method for the calculation of baseflow, Hydrolog. Sci. J., 50, 911–920, https://doi.org/10.1623/hysj.2005.50.5.911, 2005.

Quinlan, J. F. and Ewers, R. O.: Ground Water Flow in Limestone Terranes: Strategy Rationale and Procedure for Reliable, Efficient Monitoring of Ground Water Quality in Karst Areas. Fifth National Symposium and Exposition on Aquifer Restoration, Columbus, Ohio , Proceedings, 197–234, 1985.

Riedel, T. and Weber, T. K. D.: The influence of global change on Europe's water cycle and groundwater recharge, Hydrogeol. J., 28, 1939–1959, https://doi.org/10.1007/s10040-020-02165-3, 2020.

Rust, W., Holman, I., Corstanje, R., Bloomfield, J., and Cuthbert, M.: A conceptual model for climatic teleconnection signal control on groundwater variability in Europe, Earth-Sci. Rev., 177, 164–174, 2018.

Rust, W., Holman, I., Bloomfield, J., Cuthbert, M., and Corstanje, R.: Understanding the potential of climate teleconnections to project future groundwater drought, Hydrol. Earth Syst. Sci., 23, 3233–3245, https://doi.org/10.5194/hess-23-3233-2019, 2019.

Rutledge, A. T.: Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data – update, U. S. Geological Survey Water-Resources Investigations Report, 98–4148, 1998.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E. F., and Marx, A.: Anthropogenic warming exacerbates European soil moisture droughts, Nat. Clim. Change, 8, 421–426, https://doi.org/10.1038/s41558-018-0138-5, 2018.

Seidenfaden, I. K., Mansour, M., Bessiere, H., Pulido-Velazquez, D., Højberg, A., Samolov, K. A., Baena-Ruiz, L., Bishop, H., Dessì, B., Hinsby, K., Hunter-Williams, N. H., Larva, O., Martarelli, L., Mowbray, R., Nielsen, A. J., Öhman, J., Petrovic-Pantic, T., Stroj, A., van der Keur, P., and Zaadnoordijk, W. J.: Evaluating recharge estimates based on groundwater head from different lumped models in Europe, J. Hydrol.: Regional Studies, 47, 101399, https://doi.org/10.1016/j.ejrh.2023.101399, 2023.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, J. Am. Stat. Assoc., 63, 1379–1389, https://doi.org/10.2307/2285891, 1968.

Sloto, R. A. and Crouse, M. Y.: HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis, U. S. Geological Survey Water-Resources Investigations Report 1996–4040, https://pubs.er.usgs.gov/publication/wri964040 (last access: June 2025), 1996.

Smakhtin, V. U.: Low flow hydrology: a review, J. Hydrol., 240, 147–186, https://doi.org/10.1016/S0022-1694(00)00340-1, 2001.

Smart, P. L. and Hobbs, S. L.: Characterization of carbonate aquifers – A conceptual base, in: Environmental problems in karst terranes and their solutions: Bowling Green, KY, 1–14, 1986.

Teuling, A. J., de Badts, E. A. G., Jansen, F. A., Fuchs, R., Buitink, J., Hoek van Dijke, A. J., and Sterling, S. M.: Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe, Hydrol. Earth Syst. Sci., 23, 3631–3652, https://doi.org/10.5194/hess-23-3631-2019, 2019.

Tramblay, Y., Mimeau, L., Neppel, L., Vinet, F., and Sauquet, E.: Detection and attribution of flood trends in Mediterranean basins, Hydrol. Earth Syst. Sci., 23, 4419–4431, https://doi.org/10.5194/hess-23-4419-2019, 2019.

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S. M., Volaire, F., Boone, A., Le Page, M., Llasat, M. C., Albergel, C., Burak, S., Cailleret, M., Cindrić Kalin, K., Davi, H., Dupuy, J.-L., Greve, P., Grillakis, M., Hanich, L., Jarlan, L., Martin-StPaul, N., Martínez-Vilalta, J., Mouillot, F., Pulido-Velazquez, D., Quintana-Seguí, P., Renard, D., Turco, M., Türkeş, M., Trigo, R., Vidal, J.-P., Vilagrosa, A., Zribi, M., and Polcher, J.: Challenges for drought assessment in the Mediterranean region under future climate scenarios, Earth-Sci. Rev., 210, 103348, https://doi.org/10.1016/j.earscirev.2020.103348, 2020.

Vicente-Serrano, S. M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., López-Moreno, J. L., Beguería, S., Noguera, I., Harrigan, S., and Vidal, J.-P.: Climate, irrigation, and land cover change explain streamflow trends in countries bordering the northeast Atlantic, Geophys. Res. Lett., 46, 10821–10833, https://doi.org/10.1029/2019GL084084, 2019.

Vilhar, U., Kermavna, J., Kozamernik, E., Petric, M., and Ravbar, N.: The effects of large-scale forest disturbances on hydrology – An overview with special emphasis on karst aquifer systems, Earth-Sci. Rev., 235, 104243, https://doi.org/10.1016/j.earscirev.2022.104243, 2022.

Zhang, J., Liesch, T., Chen, Z., and Goldscheider, N.: Global analysis of land-use changes in karst areas and the implications for water resources, Hydrogeol. J., 31, 1197–1208, https://doi.org/10.1007/s10040-023-02650-5, 2023.