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], Jean-Baptiste Charlier[1,2]

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

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

Abstract. Long-term observations of spring discharge provide an alternative to estimate 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 karstic environments. Due to relatively short response times, karst systems are ~~focus points~~ pivotal in improving our ~~for enhancing the~~ understanding of the impact of climate change on groundwater resources. This ~~work~~ study analyses observational data (precipitation, temperature and discharge) ~~of more than~~from over 50 springs ~~spatially~~ distributed ~~over~~ across Europe (AT, FR, GB, SI), offering a ~~to give a~~ continental ~~overview~~ perspective ~~of changes in~~on groundwater resource changes~~s~~ in karst areas. The work focuses on two ~~different~~ periods spanning~~of~~ 20 and 40 years, aiming to detect ~~to identify any~~ possible accelerations or moderations in ~~changes~~trends over time. For both periods, ~~a~~ trend analyse~~i~~s of the observational data were conducted~~,~~ using the Mann-Kendall test and Sen's slope~~,~~ on full time series as well as seasonal data ~~was performed on the entire time series and per season~~. Additionally, potential ~~Possible~~ process changes were ~~considered~~ examined through~~by analysing also~~ trends in high and low flow values. Structural differences ~~of the~~among karst systems were accounted for~~considered by~~ using two indices related to ~~the~~ storage and inertia of the system. which were used to i) highlight structural differences and ii) classify karst systems accordingly.~~In combination, these indices were able to i) highlight structural differences and ii) characterize 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 ~~calculated~~ observed in this study align with~~follow~~ the general patterns of river discharge found in literature.~~,~~ However, the behaviour during ~~but~~ the last 20 years ~~deviate~~ diverges from ~~this~~these historical patterns ~~behaviour~~. ~~During~~ In this most recent ~~this~~ period, increasing temperatures play~~s~~ a more significant~~important~~ role in the evolution of spring discharge than changes in precipitation. These ~~results~~ findings are contextualized with consideration of~~are discussed in relation to the~~ indirect drivers, ~~influence of other drivers~~ such as changes in land use or land cover, specific regional conditions, and shifts in~~but also changes in processes related to~~ groundwater recharge and storage processes. Together, they offer valuable ~~, providing~~ insights for assessing groundwater recharge in the past and in the future.

1 Introduction

The impact of global change on fresh water 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 manifold 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~~In addition~~, the absence of direct, spatially distributed ~~direct~~ measurements of ~~spatial distributed~~ actual recharge complicates the identification of regional trends, even when ~~are not possible. This makes it difficult to identify trends on regional scale even by analyzing~~ a comprehensive global data set of groundwater recharge measurements is analysed (Moeck et al., 2020).

Hydroclimatic conditions, e.g. precipitation and temperature, are generally~~usually~~ considered as primary ~~main~~ drivers of land surface water fluxes ~~and~~ making~~e~~ groundwater recharge highly susceptible~~vulnerable~~ to climate change (Mohan et al., 2018). ~~However,~~ O~~o~~ver recent~~the last~~ decades, however, human activities – such as~~impact on groundwater recharge~~ increased ~~due to changes of~~ 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). ~~The latter is closely connected to net increases in evaporation.~~ In many~~large~~ 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 ~~point~~ for assessing long-term changes ~~studying changes~~ in water resources.

Long-term spring discharge observations ~~of spring discharge~~ provide an alternative means of~~to~~ estimating~~e~~ ~~the evolution of~~ groundwater resources evolution ~~based on observational data~~ at catchment scale. ~~In this context,~~ K~~k~~arst aquifers, in particular, ~~appear to be~~ are of ~~s~~significant~~pecial~~ interest due to their unique~~specific~~ properties, closely related to the soluble (carbonate) rocks, generating a hierarchical organised groundwater drainage network over large areas (e.g. Palmer, 1991, Ford and Williams, 2007). Therefore, continuous measurements of karst spring discharge offer~~give~~ a holistic output signal of the aquifer system integrating the various ~~combining all the~~ processes that transform~~ing~~ the recharge signal as is propagates ~~on the way~~ through the system to the outlet. ~~Different to~~ Unlike most other types of aquifer systems, groundwater ~~recharge~~ flow in karst areas is thus highly influenced by differences in hydraulic properties (channels/conduits vs. fractured/porous matrix) ~~preferential flow in fissures and open conduits~~ and needs to be divided into concentrated and diffuse processes (e.g. Hobbs and Smart, 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 ~~Concentrated infiltration into the system generally leads to~~ fast flow dynamics ~~which~~ make~~s~~ it potentially possible to detect the impact of ~~changes in~~ groundwater recharge on water resources. ~~Following this reasoning~~ Consequently, spring discharge can be used as a robust regional climate indicator (Fiorillo et al., 2021) and ~~due to their sensitivity~~, karst aquifer, due to their sensitivity, can be sentinels of global changes (Binet et al., 2020; Binet et al., 2022).

In Europe, karst outcrops cover an absolute area of approximately 2.17 million km² accounting for ~~a total area share of~~ 21.8 % of the continent's total area (Goldscheider et al., 2020). The contribution of water from karst areas to ~~the~~ national fresh ~~h~~ water supply varies widely, ranging from ~~between~~ 5% to~~and~~ 50% (Hartmann et al., 2014), making karst aquifers together with alluvial formations to the most ~~efficient~~ important source of fresh water (Bakalowicz, 2005). For water management ~~purposes~~ and ~~but also securing~~ 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 flood in karst systems can cause hazards for 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 s~~S~~pring discharge analysis is a common tool for~~to~~ characterizing~~e~~ karst systems, it ~~but~~ can also be used to analyse changes in hydroclimatic conditions or ~~calculated~~ recharge values. Over a long period, ~~discharge of~~ European karst spring discharge~~s~~ seems to decline due to~~caused by~~ rising temperatures, and the consequent reduction of 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 pattern. 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 ~~Other studies from European karst areas highlight the influence of~~ 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. ~~These influences have the ability to mask the long-term influence of climate change on spring discharge. Furthermore~~, ~~several~~ 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 ~~.~~ n~~N~~egative (winter) NAO values correlating with increased spring discharge ~~have been resulting in an increase in spring discharge~~ since around~~roughly~~ 2008 ~~correlated to~~ (De Vita et al., 2012; Fiorillo and Guadango 2012; Fiorillo et al., 2015; Fiorillo et al., 2021). However, the influence of various ~~different~~ large-scale atmospheric circulations results in ~~influence the discharge from Italian karst springs resulting in a~~ complex periodicities~~y~~ ranging from biennial~~two years~~ to multi-decadal cycles (De Vita et al., 2012). According to the latter~~authors,~~ the impact on spring discharge is high, accounting for a variability of roughly 30%. Differences in the response of the karst systems are 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, the c~~C~~hanging hydroclimatic conditions are expected to increasingly threaten~~thus projected to jeopardize ~~ fresh water resources in most karst areas in Europe by reducing ~~absolute ~~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 affects karst water resources and therefore the reliable water supply to millions of people negatively. 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 spatially distributed over Europe. This study is a multi-decad~~n~~al trend analysis of hydroclimatic observational data for European karst systems and designed to answer the following research questions:

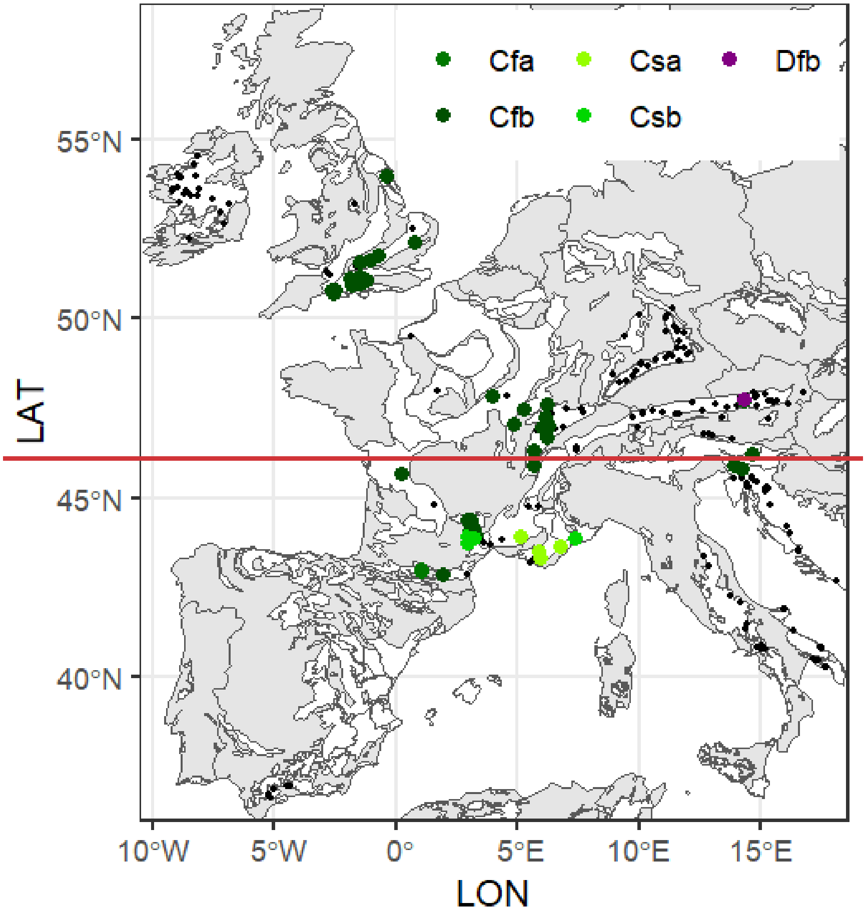
- Does discharge from European karst areas change uniformly over time or is it possible to detect regional patterns?
- Does variability ~~significant changes ~~in ~~overall spring ~~discharge have an impact on low and high flow conditions?

~~Is it possible to identify sets of karst storage properties which are particularly sensitive to climate change?~~

- Is it possible to identify karst areas with certain properties related to storage which are particularly sensitive to climate change

2 Data and methods

Karst outcrops drained by major karst springs are widespread across ~~can be found in large parts of ~~Europe (Fig.1; Chen et al., 2017) ~~covering ~~spanning all climate zones of the mid~~-~~latitudes. Hydroclimatic conditions, combined ~~together ~~with~~ the~~ geological history, play an important role in the evolution of karst aquifers ~~leading to~~resulting in a complex pattern of systems on a continental scale. To evaluate the impact of changing climatic conditions on~~f~~ different types of karst systems, this study ~~focuses on~~examines ~~publically~~publicly available spring discharge data from ~~several ~~multiple European countries. To ~~be able to analyse~~assess potential ~~possible impacts of ~~climate change impacts on karst groundwater resources ~~during the last~~over recent decades, the following method was applied. Long-term trends in karst spring discharge were ~~assessed ~~analysed for all European springs with time series ~~fulfilling ~~meeting the requirements ~~indicated ~~outlined in section 2.1. The assessment ~~was~~ focused on ~~performed over ~~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 ~~two investigated periods are, first a~~ period spans~~of~~ 40 years (starting at 01.01.1982) to capture~~over~~ long-term trends, while the~~ and~~ second covers~~a~~ shorter period of 20 years (starting date: 01.01.2002). The shorter period enables the examination of a shorter timeframe, comparable to those described for Italian karst springs (e.g., Fiorillo et al., 2021).~~allows for an investigation of ~~changes on the same time scale that those described for Italian karst springs (e.g. Fiorillo et al., 2021).Changes were evaluated~~analysed~~ using the Mann-Kendall test and Sen's slope computation (Section 2.3) for both monthly spring discharge and annual extremes, expressed as~~by~~ different quantiles, namely the 10th and 90th quantile. ~~The two investigated periods are, first a period of 40 years (starting at 01.01.1982) to cover long-term trends and second a shorter period of 20 years (starting date: 01.01.2002). The shorter period allows for an investigation of changes on the same time scale that those described for Italian karst springs (e.g. Fiorillo et al., 2021). Further~~Additionally, trends in monthly precipitation and temperature were computed ~~on monthly precipitation and temperature~~ to identify changes in the input signal of the systems. To further investigate~~explore~~ the influence~~mpact~~ of groundwater dynamics on observed trends, two specific indices - -related to storativity and inertia (Section 2.1.1/2.1.2) - were calculated for each period.



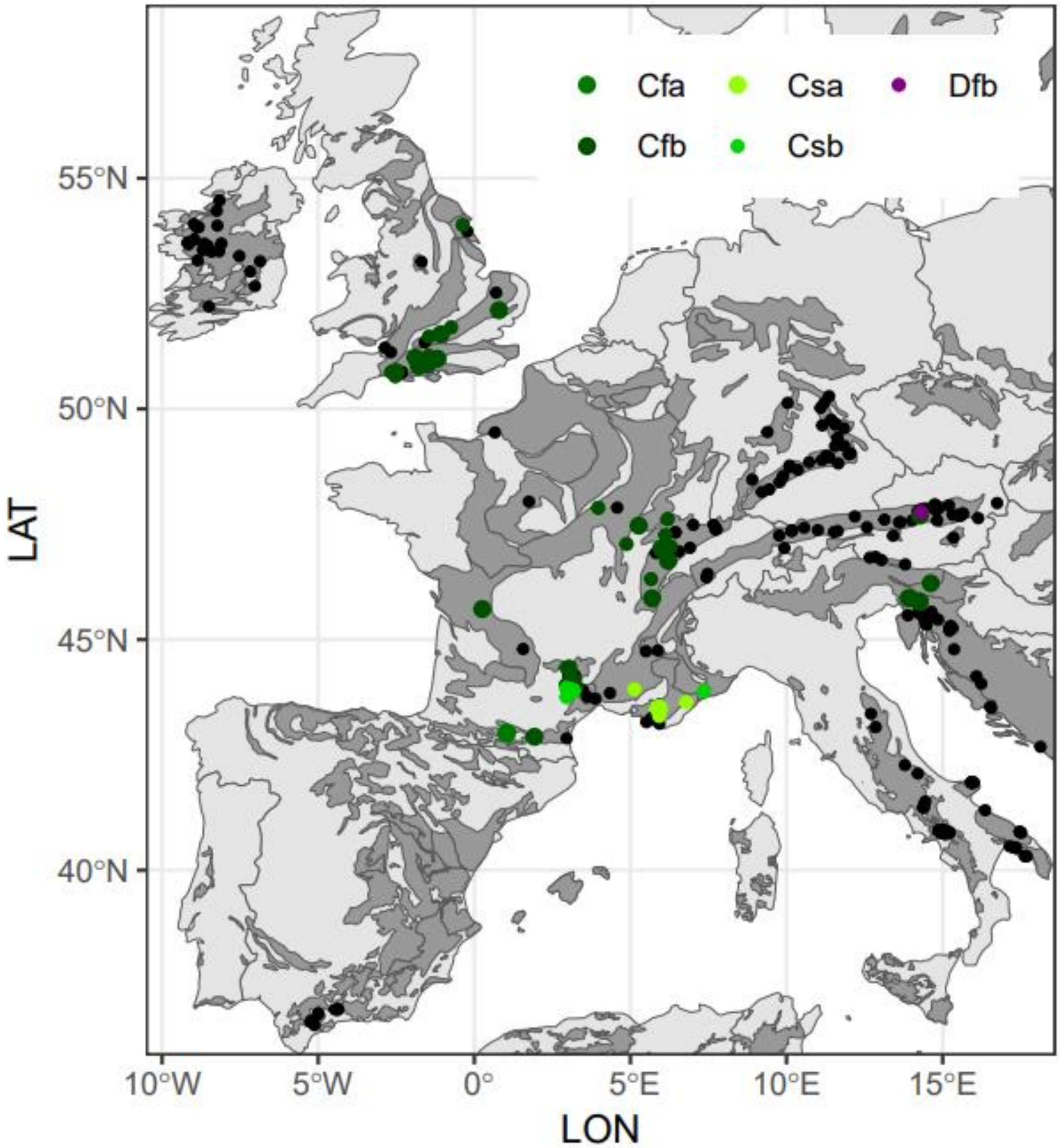


Fig 1: Karst spring location (black dots) according to the WOKAS database (Olarinoye et al., 2020) and carbonate rock outcrop (white area) in Europe according to WoKaM (Chen et al., 2017). Springs used in this analysis are coloured. Colours indicate the climate zone according to the Koepper-Geiger classification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

2.1 Karst spring discharge

Spring discharge data were ~~derived~~ obtained from the World Karst Spring Hydrograph dataset (WOKAS; Olarinoye et al., 2020) and the French national database Hydroportail (https://www.hydro.eaufrance.fr/). The WOKAS dataset ~~combines~~ aggregates spring discharge data from national agencies ~~as well as~~and time series collected by ~~many~~ various research groups ~~around the~~ worldwide. In both databases, spring discharge is ~~considered in its broadest sense~~interpreted broadly, ~~which~~

~~means~~meaning~~ that~~ measurements ~~might ~~may have been ~~also be~~ taken ~~ further ~~downstream of the spring itself. From both datasets, all time series ~~satisfying ~~meeting the minimum requirements for the two periods - ~~of ~~20 years (starting at 01.01.2002) and 40 years (starting at 01.01.1982) - were selected. The minimum requirements were a) continuous daily measurements ~~with~~ and b) less than 10% ~~of ~~missing data over the respective 20- ~~respectively ~~and 40-year periods. No~~ further~~ pre-processing, for example the interpolation of missing data, was ~~done ~~performed prior the analysis. In total 54 springs from four ~~4 different~~ countries satisfied the requirements for the shorter period, and 22 springs from four ~~ different ~~countries ~~fit the requirements for the short, respectively ~~met the criteria for the longer period (Fig. 1)~~the long period (Fig. 1)~~. Detailed information on spring names, time series, and locations is provided in Table 1~~Spring names and basic information regarding the time series and location of the spring can be found in Table ~~1. Note that nine~~9~~ time series from French springs start during the first or the second year, while all other time series were ~~unified ~~aligned to start ~~at ~~on ~~the 1st of ~~January 1 and end 20 or~~ respectively~~ 40 years later (~~,~~on ~~the 31st of ~~December 31, 2021). For Austrian springs, data were~~is~~ 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~~ located~~ in other ~~different ~~climate zones include those ~~can be found ~~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, particulartly~~mainly~~ in Austria and the Grands Causses region in Southern France, are located along climate zone boundaries.

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 on the 40-year period or for shorter time series on 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)	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

Monthly mean discharge was calculated for each spring (Table 1) and used in~~for~~ the trend analysis. Additionally~~Further~~, trends were calculated for the annual minimum and maximum flow. These values were derived by ~~accumulating~~ aggregating ~~the~~ discharge below the 10^{th} quantile (Q10) and ~~respectively~~ above the 90^{th} 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. ~~In general,~~ K~~k~~arst systems are generally classified ~~based on the description of~~according to flow patterns~~,~~ (e.g. Mangin, ~~(~~1975; ~~) or~~ Quinlan and Ewers, ~~(~~1985), which are a combination of dominant recharge processes, storativity and flow dynamics within ~~of~~ different karst system compartments (Hoobs and Smart, 1986). All these factors ~~highly depend~~are strongly dependent on the 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 ~~frequently~~ commonly used indices were computed.

Firstly, to assess~~describe~~ the storage capacity of karst systems, daily discharge was filtered to separate quick and slow flow components and to therefore compute the baseflow index (BFI). Traditionally, the slow flow component is interpreted as baseflow (Smakhtin, 2001), in karst hydrology 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~~Many different separation methods 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 ~~chosen~~selected, implemented in~~using~~ the R package *BFI* (Ladson et al., 2013). This method can be described as a smoothing algorithm using~~es~~ 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 focus 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 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 ~~of the karst systems~~ was calculated. This~~It~~ is determined ~~by~~ using a threshold of 0.2 in the autocorrelation function below which the signal is considered ~~as~~ i~~u~~ndistinguishable from noise (Mangin, 1984). The memory effect ~~has been~~is widely used to characterize ~~the~~ storativity in~~of~~ karst systems and to compare response times across~~between different~~ 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 ~~derived~~ from the daily gridded observational dataset for Europe (E-OBS; Cornes et al 2018). The E-OBS dataset provides hydroclimatic data with a spatial resolution of a 0.1-degree regular grid, based on the interpolation of observations ~~hydroclimatic variables~~ from a network of European meteorological stations. ~~Currently,~~ T~~t~~he dataset currently spans ~~covers~~ the period between 1950 and 2022. For ~~every~~ each karst spring, ~~the~~ climate variables were extracted~~selected~~ 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, ~~This means that~~ in areas with high spring density, one single grid cell ~~can~~ may represent the hydroclimatic conditions~~variables~~ for multiple ~~more than one~~ springs.

For trends analysis, daily precipitation values were summed, and daily temperature values were averaged to calculate monthly and seasonal values.

~~Daily values of precipitation and temperature were accumulated respective averaged to obtain monthly and seasonal values~~. ~~Even~~ Although the study encompasses a range of climate zones across Europe~~covers entire Europe and therefore different climate zones~~, standardized meteorological seasons (winter: DJF, spring: MAM, summer: JJA, and autumn: SON) were used for consistency~~comparison purposes~~.

2.3 Trend analysis

The Mann-Kendall test (Kendall 1948; Mann, 1945) is a widely ~~frequently~~ used method for ~~the~~ trend analysis of observational data and climatic indices. This includes analysis of the~~the observational~~ E-OBS dataset, which has been ~~analysed~~ evaluated at various temporal resolutions such as ~~for different timely resolution for example~~ monthly, seasonal, and annual scales~~yearly before~~ (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 ~~calculated for~~applied to spring discharge and hydroclimatic variables. The ranked-based, non-parametric Mann-Kendall test ~~determines~~ assesses the significance of monotonic trends by ~~comparing the~~evaluating differences between ~~measurements~~ earlier and later measurements in the time series. As a non-parametric test, it is suitable for data with ~~it can be used for time series with~~ non-normal distributions and is, therefore, commonly~~often~~ 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 ~~overcome~~ address~~the~~ sensitivity to~~of the~~ confidence level~~s of the Mann-Kendall test~~, two significance thresholds were used:~~different statistical significance level were set, the first one with~~ a p-values of 5 %, and ~~the second one with p-values~~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.~~Sen's slope (Sen, 1968) is used to calculate the sign and slope of the calculated trend.~~ The Mann-Kendall test and Sen's slope were chosen for their widespread use in monotonic trend analyses~~were used because they are frequently applied for monotonic trend analysis~~ in both climatic and hydrological contexts~~studies~~. 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~~, and hence applicable to non-normal distribution as found for monthly discharge data from karst springs~~ (e.g. Fiorillo et al., 2021). Both statistical tests are included in the R package *modifiedmk* (Hamed and Rao, 1998).

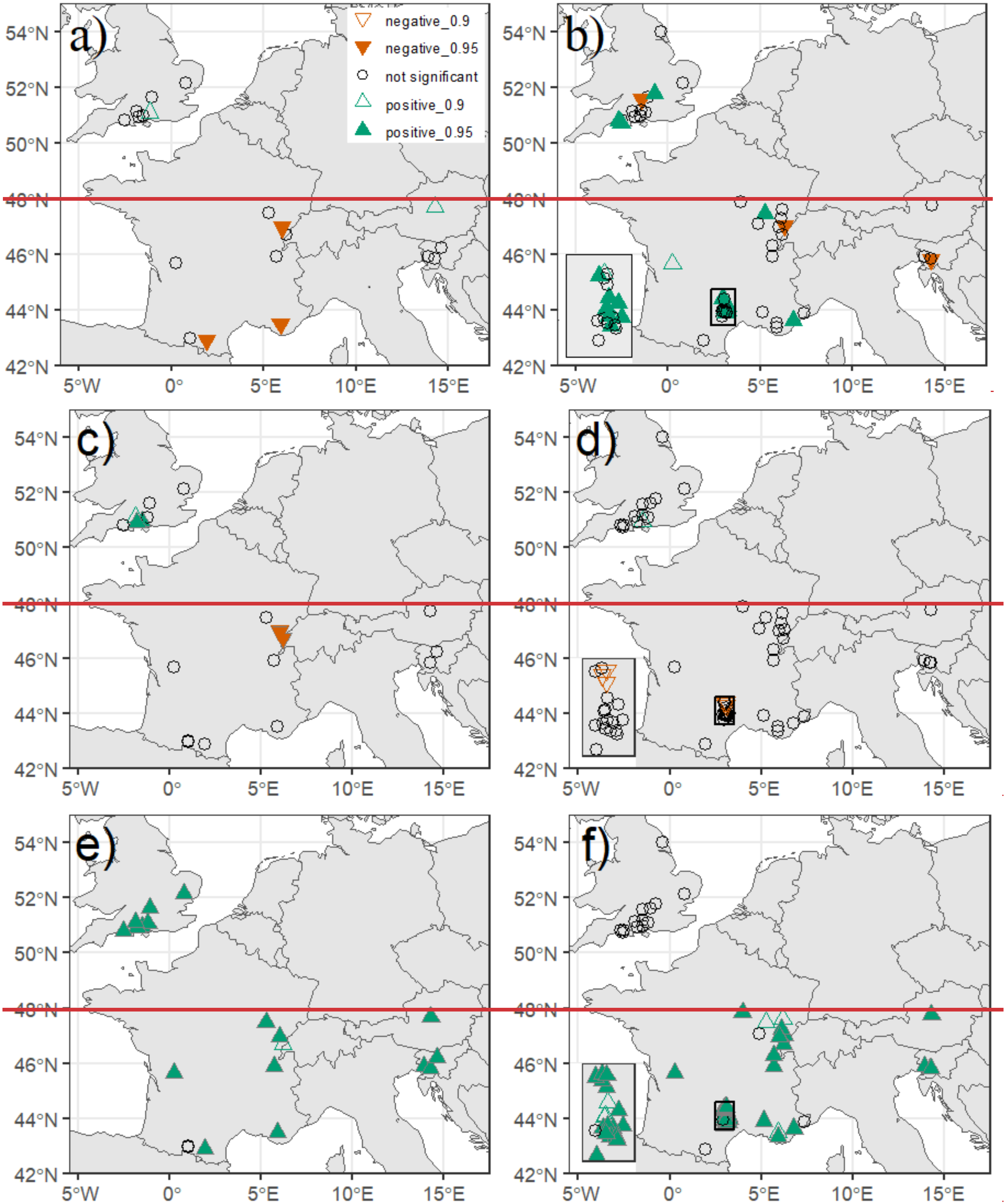
3 Results

3.1 Trends in monthly spring discharge and climate variables

Only six of the analysed springs exhibit significant changes in discharge over the p~~l~~ast 40 years (Fig.2a). Among these, t~~T~~he three springs with decreasing trends ~~negative changes~~ show ~~have a~~ higher significance (at the 5% probability level) compared to the two springs with increasing trends ~~than the two positive ones~~ (at the 10% probability level). With the exception of ~~Apart from~~ two springs, all springs with ~~discharge records of~~ 40~~-~~ years discharge records are located in the temperate climate zone (Cfb). Of the exceptions, ~~Both springs,~~ one spring is situated~~located~~ in the Mediterranean climate zone (Csa), and the other ~~one~~ in the humid subtropical climate zone (Cfa). Both ~~, have decreasing~~show decreasing spring discharge. The latter ~~one~~ spring (~~spring~~ Fontestorbes) ~~is one of the springs draining~~ drains a mountainous catchment in the Pyrenees. The other two springs with decreasing spring discharge (~~spring~~ Lison and Verneau) are located in the French Jura mountains, which is also ~~also drain karst systems in~~ a mountainous region~~, the French Jura mountains~~. In contrast, the Spring Pissling 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 Cheriton Spring in England.~~The only other spring located in a mountainous region is the spring Pissling Ursprung, draining a karst system on the northern side of the Austrian Alps. This spring is one of two springs with increasing discharge trends. The other one is in England (spring Cheriton).~~

Discharge trends ~~of~~ over the p~~l~~ast 20 years (Fig. 2b) differ both locally ~~but also on a~~and continentally~~ scale~~ from the long-term trends. Positive trends are dominant in large parts of Europe. Of the~~Out of~~ 15 springs with positive trend, one~~ each~~ is in the Csa and another in the Csb climate zone, while the remainder are in the Cfb zone~~and Csb climate zone, the rest are in the Cfb~~

~~climate zone~~. Many of these springs are located in the Grands Causses region~~Most of them are karst springs 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 showed significant trends over the 40-year period exhibit significant changes during the shorter 20-year period.~~Apart from there, positive trends can also be found in other parts of France and in England. Three springs have a negative sign in discharge, spread out over Europe. In addition, none of the springs with trends over the 40-year period has any significant changes in the 20-year period.~~


a)
b)
c)
d)
e)
f)
negative_0.9
negative_0.95
not significant
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54°N
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50°N
48°N
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5°W
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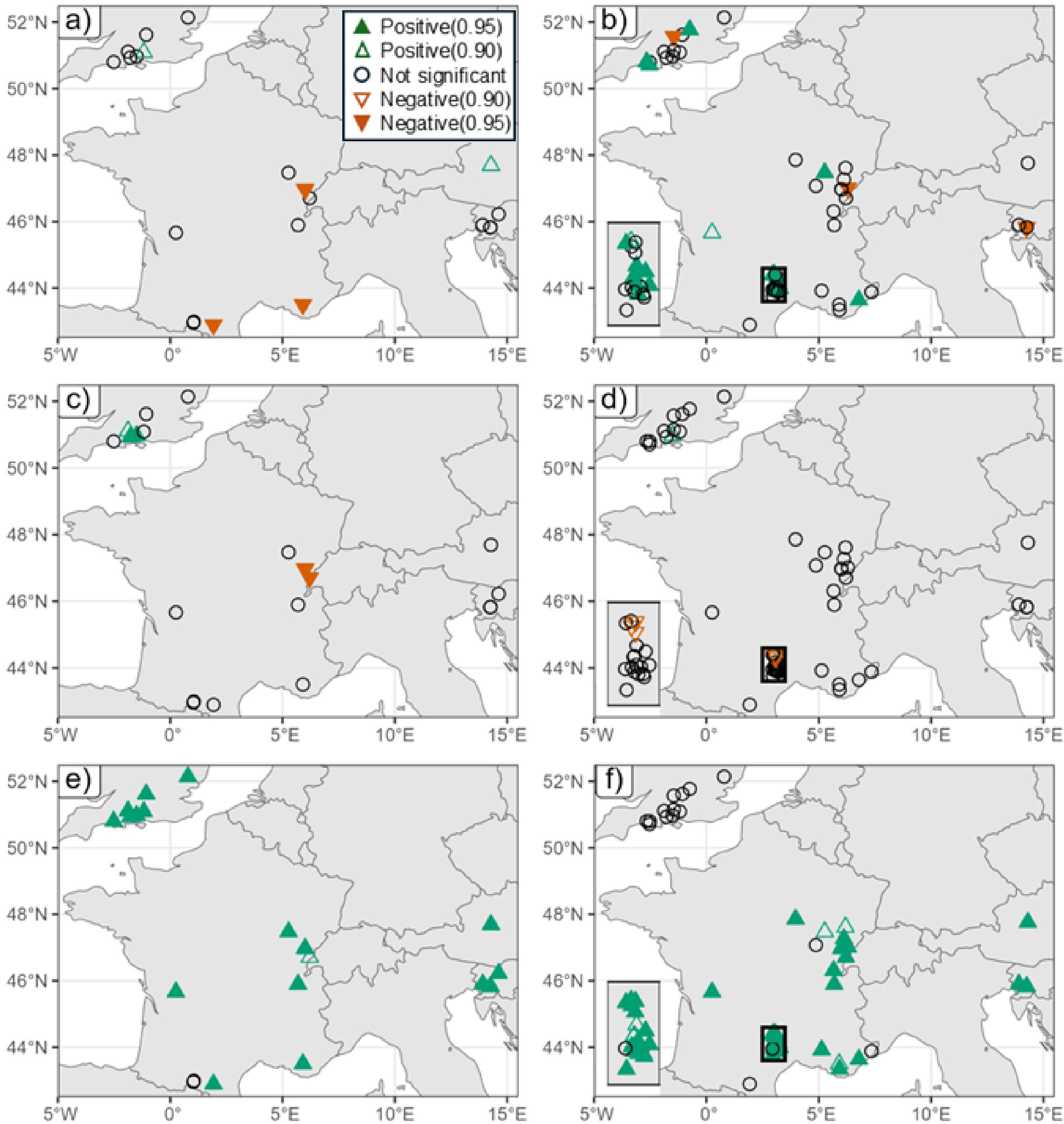


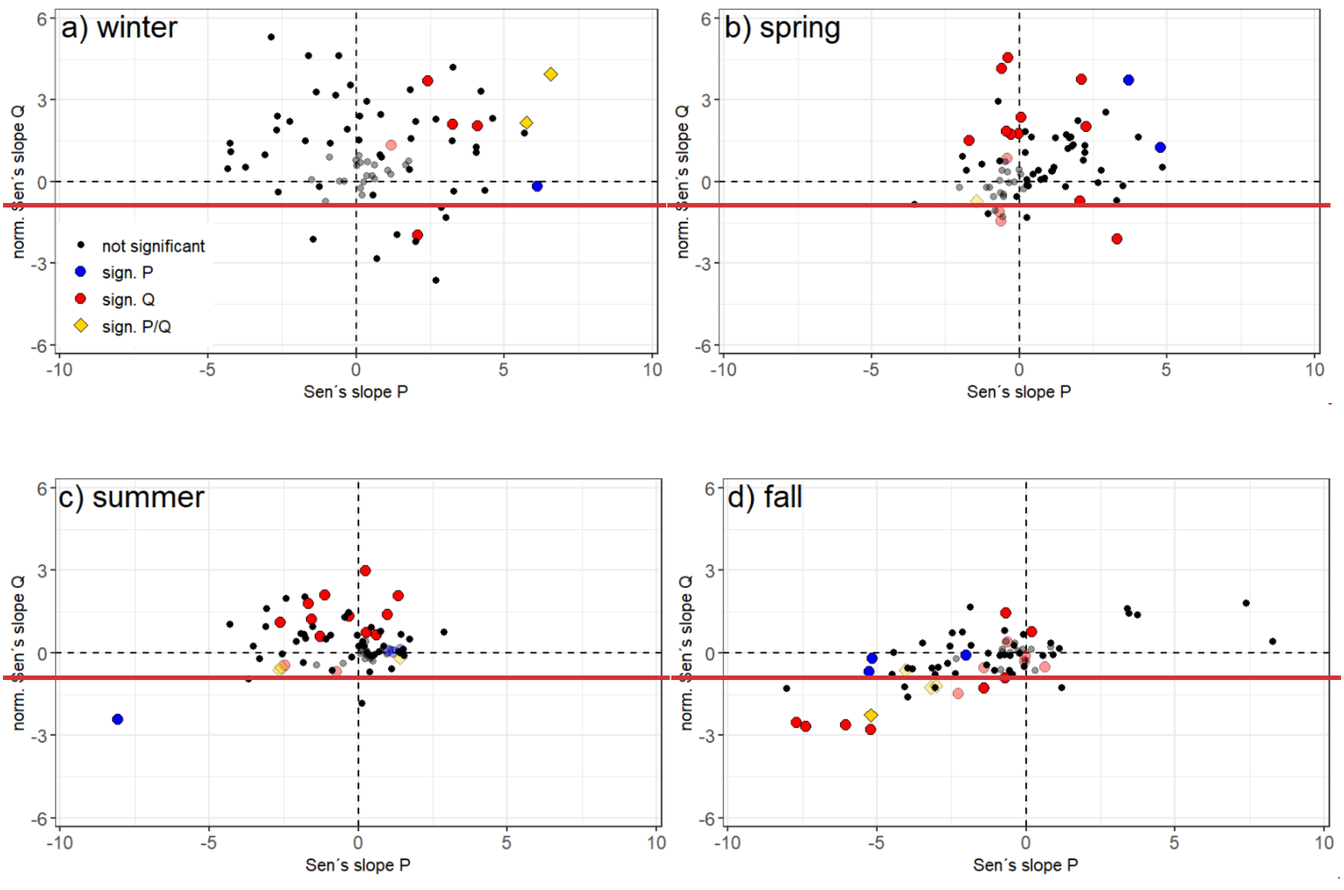
Figure 2: Trends in discharge (a,b), precipitation (c,d) and temperature (e,f) over the 40-year (1982-2021 – left) ~~respectively~~ and the 20-year (2002-2021 – right) period, respectively. Red symbols indicate negative trends while green symbols indicate positive trends.

Despite the number of springs with significant discharge trends ~~in discharge~~, precipitation remains relatively ~~is rather~~ stable over both periods, with changes occurring only~~. As presented in Fig 2c) and d), precipitation changes only~~ locally (Fig 2c and d). Over the 40-year period~~ of 40 years~~, significant precipitation trends are detected in just six karst areas represented by E-OBS grid cells~~only 6 karst areas, represented by EOBS grid cells, have a significant precipitation trend~~. Three of these are~~locations can be found~~ in southern England near the region of the Cheriton spring, although the grid cell containing the spring itself does not show a significant increase.~~in the same area of the spring Chariton. However, the exact location of the Chariton station does not show a significant increase.~~ The only region with a negative precipitation trend~~s~~ is the French Jura mountains, where two springs ~~of the springs~~ with negative discharge are located. Over the last 20 years, the negative precipitation trend in the Jura Mountains ~~is~~ has slowed~~, down~~ and no significant changes ~~can be~~are detected in this area. Further south, in the Grands Causses region, ~~precipitation decrease in the far north of the region, however only at the lower significance level~~ a decrease in precipitation is observed in the far north of the region, but only at a lower significance level. The number of positive trends in UK grid cells ~~located in the UK~~ also decreases, with just one grid cell showing a ~~to one with~~ lower significance level.

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

3.2 Seasonal changes in monthly spring discharge and climate variables

Spring discharge varies widely ~~between~~ among European karst spring (see Tab. 1). To account for~~ the~~ differences in mean discharge, a normalized Sen´s slope (seasonal Sen´s slope/Q_{mean}) ~~for discharge~~ was used to analyse changes in seasonal discharge on the continental scale. In Figure 3, the top-right and bottom-left corners of each seasonal subplots indicate similar positive and negative Sen´s slopes for normalized seasonal discharge (Q) and seasonal precipitation (P), respectively. For ~~simplification reasons~~simplicity, all locations are summarized in a single plot ~~the same~~ irrespective of their climatic zones~~plot regardless the climatic zone they belong to~~. Based on the results presented in Figure 2, air temperature was excluded from the seasonal analysis because its uniform increase across all seasons and springs was not considered a key factor influencing inter-annual discharge variability.~~Following the results of Fig. 2, air temperature was not included in the seasonal analysis, assuming that its global increase for all spring was not a key explaining factor for inter-annual variability of discharge.~~


a) winter
b) spring
c) summer
d) fall
norm. Sen´s slope Q
Sen´s slope P
not significant
sign. P
sign. Q
sign. P/Q

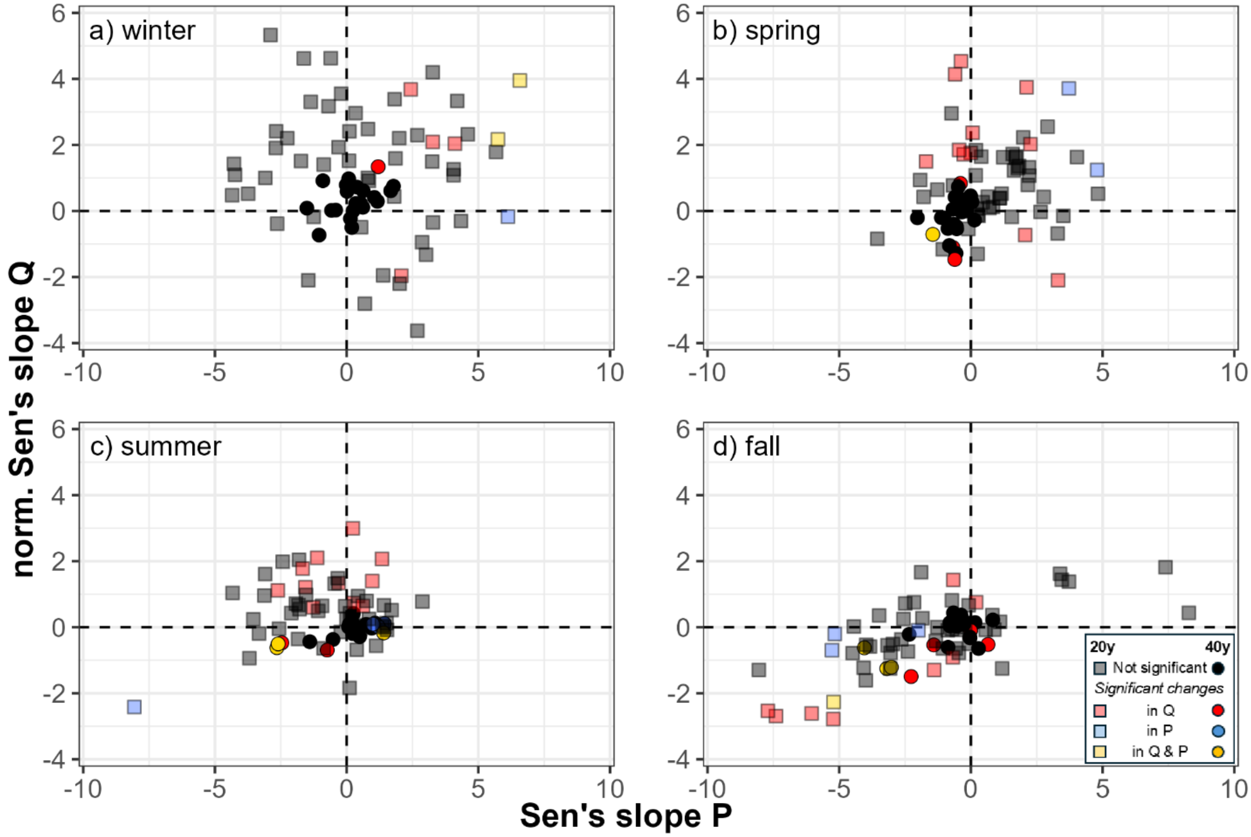


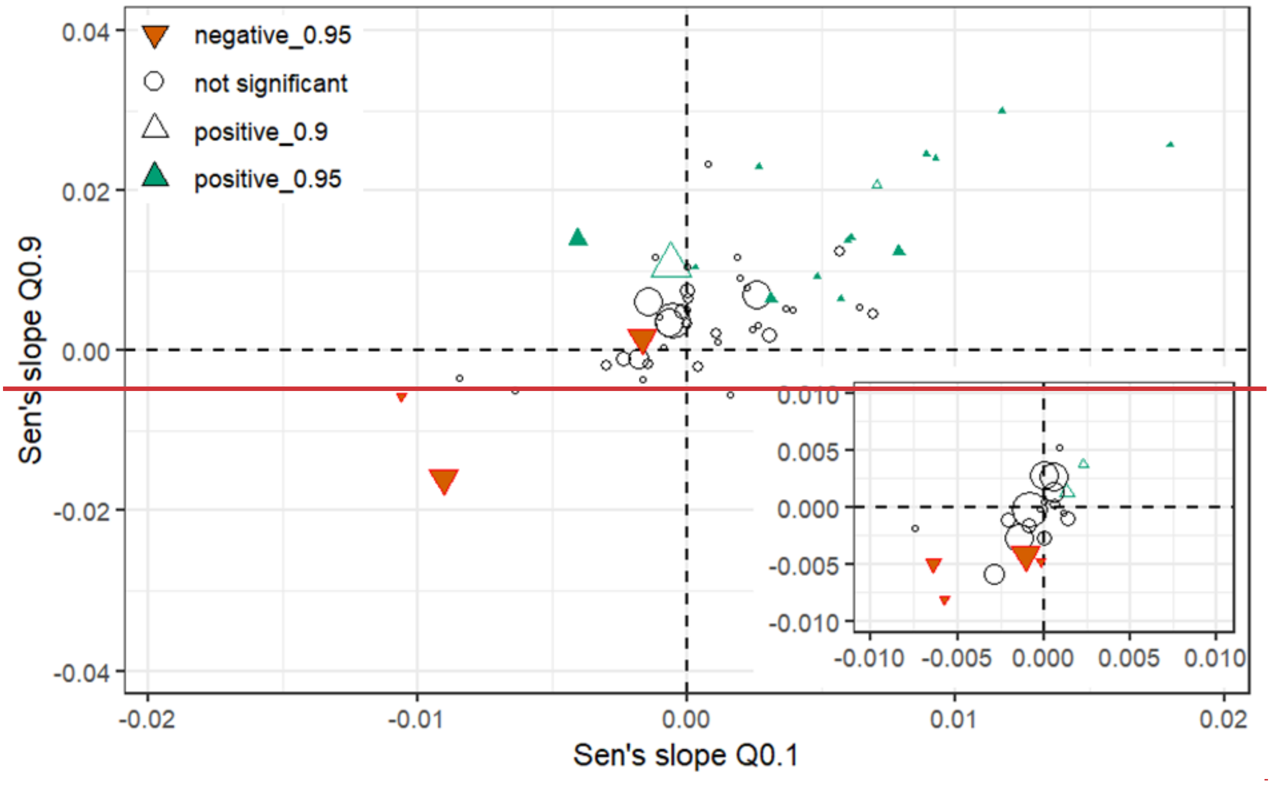
Figure 3: Comparison of changes in precipitation and discharge trends for a) winter, b) spring, c) summer, and d) fall. Springs indicated by red dots have significant changes in discharge, by blue dots in precipitations and diamonds have significant changes in both seasonal precipitation and discharge. ~~**Bold symbols represent the 20-year period.**~~

Overall, significant simultaneous changes in both P and Q ~~at the same time~~ are rather ~~few~~ rare,~~and occur~~occurring at only ~~at~~ 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 show similar directions.~~With one exception (in summer over the 40-year period) the signs of these significant trends in precipitation and discharge are similar. Overall,~~ S~~s~~ignificant changes in Q are more prevalent, ~~are predominant~~ but the direction of these trends varies widely among ~~sign shows a high variation among~~ springs and seasons. Winter is the season with the least significant changes ~~over~~ in both periods but it shows~~and~~ the greatest ~~highest~~ variation in Sen´s slopes for both discharge and precipitation trends. ~~However~~Despite this, most springs have positive Sen´s slopes, indicating ~~and therefore~~ an overall increasing trend in discharge during winter. Precipitation trends in winter, however, show a wide range of negative and positive values.~~Sen´s slopes of precipitation changes range widely between negative and positive values~~. ~~In terms of sign and overall trends,~~ T~~t~~here are no major differences in the sign or overall trends between the two periods. However, the magnitude of changes is much greater in the ~~highly elevated during the~~ short period, a pattern observed ~~which can be found~~ in all seasons except ~~o~~for fall, where the ~~for which variations in the~~ long period also shows ~~are~~ high ~~as well~~variability. However, ~~at least~~ in winter most changes are not significant. In contrast, s~~S~~pring and summer seasons ~~,~~ ~~on the~~

~~other hand,~~ display ~~show~~ a clear increase in ~~of~~ significant discharge changes ~~during~~ over the last 20 years, ~~.~~ with the majority of these changes being significantly positive. ~~For both seasons, most of these changes are significantly positive.~~ Precipitation trends, however, show no clear pattern, although spring appears ~~Clear trends in precipitation are missing, even though spring seems to become~~ slightly wetter and summer drier on a continental scale. In these two~~both~~ season, differences between the springs are minor compared to ~~the~~ winter. The most pronounced trend ~~The clearest trend of all seasons~~ is ~~the~~ a ~~precipitation~~ decrease in precipitation during fall, often combined with a dominant decrease in discharge. This~~ese~~ trend~~s~~ is evident in ~~are equally developed for~~ both periods, though slightly amplified ~~for~~ in the last 20 years. Therefore, it can be concluded ~~stated~~ that ~~the~~ fall is the only season with a clear long-term connection between precipitation and discharge, indicating ~~with~~ 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 quantile~~percentile~~ of spring discharge ~~is done~~. In Figure 4, trend changes are expressed by Sen’s slopes in m^3y^{-1}, with changes in high flow (Q0.9) and low flow (Q0.1) ~~flow~~ 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. ~~Relative changes in annual high and low flow discharge and annual discharge are difficult to compare since the spring differ in discharge dynamics influencing mean annual discharge (cf. Table 1). Therefore~~For this reason, ~~again~~ normalized values are used in Figure ~~.~~4. The figure is divided into ~~consists of~~ four ~~different~~ quadrants where the upper-~~-~~right and lower-~~-~~left represent a unison shift of 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).



negative_0.95
not significant
positive_0.9
positive_0.95
0.04
0.02
0.00
-0.02
-0.04
Sen's slope Q0.9
-0.02
-0.01
0.00
0.01
0.02
Sen's slope Q0.1
0.010
0.005
0.000
-0.005
-0.010
-0.010
-0.005
0.000
0.005
0.010

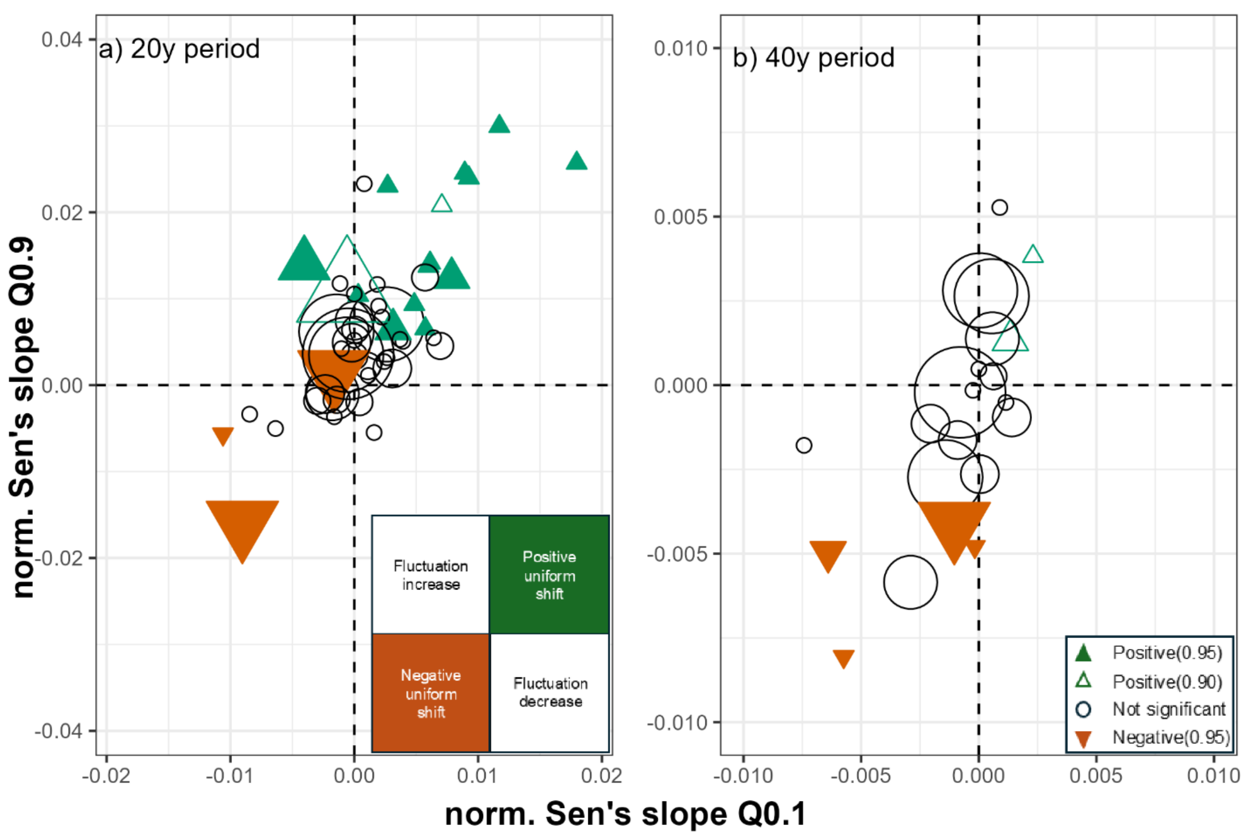


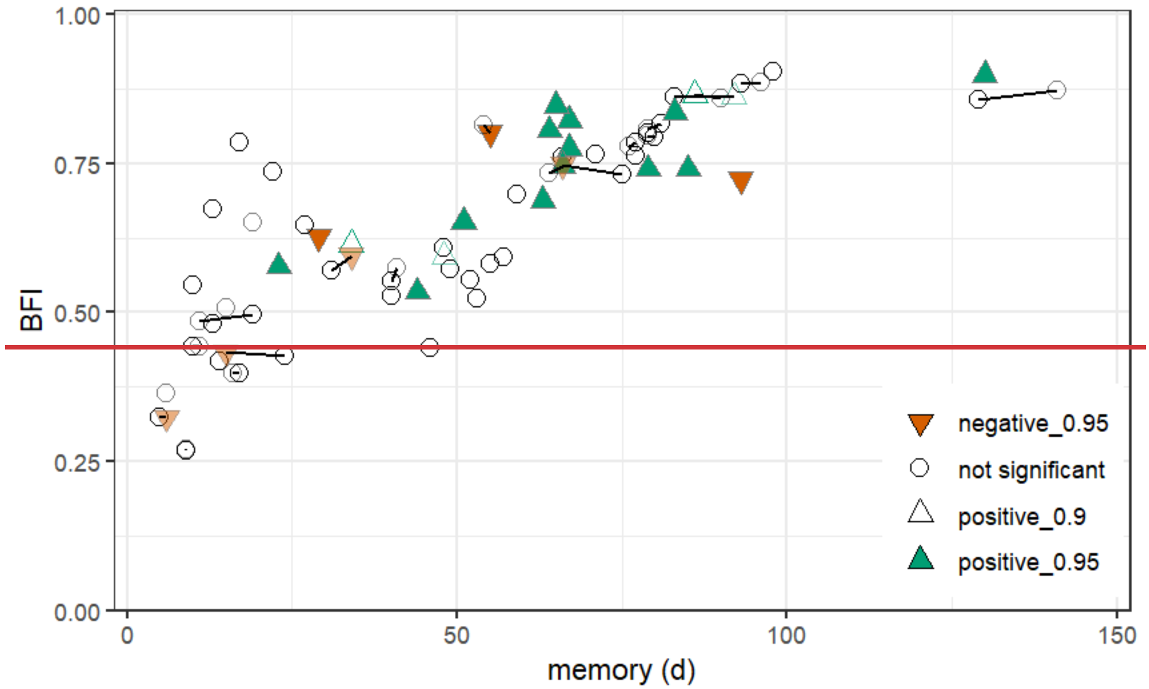
Figure 4: Distribution of high flow (Q0.9) and low flow (Q0.1) trends for a) the 20year period and b) the 40year period. Shape and colour of the symbols refer to the monthly discharge trends presented in Figure 2a and b. The size of the symbols represents the size of the spring expressed by Q_{mean}.

Comparing the trend development of extremes between the two different periods providesgives valuable insightsinformation inton recharge patterns. For springs with significant changes in annual spring discharge over the last 40 years, the entire spring discharge shifts uniformlyson either to a lower or higher stage, depending on sign direction of the global trend. All springs with negative trends in annual discharge are located in the bottom–left quadrant, which is associated with discharge decreases in both low and high flow. Also Mmost other springs without significant trend also follow this pattern and can be found either in the top--right or bottom--left quadrants. Only two springs deviate differ from this general pattern, showing a slightly negative Sen's slope for high flow discharge in connection toalongside positive low flow discharge. For the 20-year period, several springs deviate from this distribution including three with significant changes in annual spring discharge. All of these springs are located in the top–left quadrant, where with 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, whereas while one spring even shows a significant decrease in annualing spring discharge despite the increase in high flow discharge. All other springs, located in the lower lower-left or upper upper-right quadrant are following the pattern observed infor the long 40-year period.

Springs with significant increasing discharge trends are found exclusively -in the upper-right quadrant, while those with ~~and~~ decreasing trends are located ~~can be~~ solely~~ found~~ ~~in the upper right quadrant and~~in the ~~lower~~ lower-left quadrant~~, respectively~~.

3.4 Sensitivity of different karst systems to changing climatic conditions

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



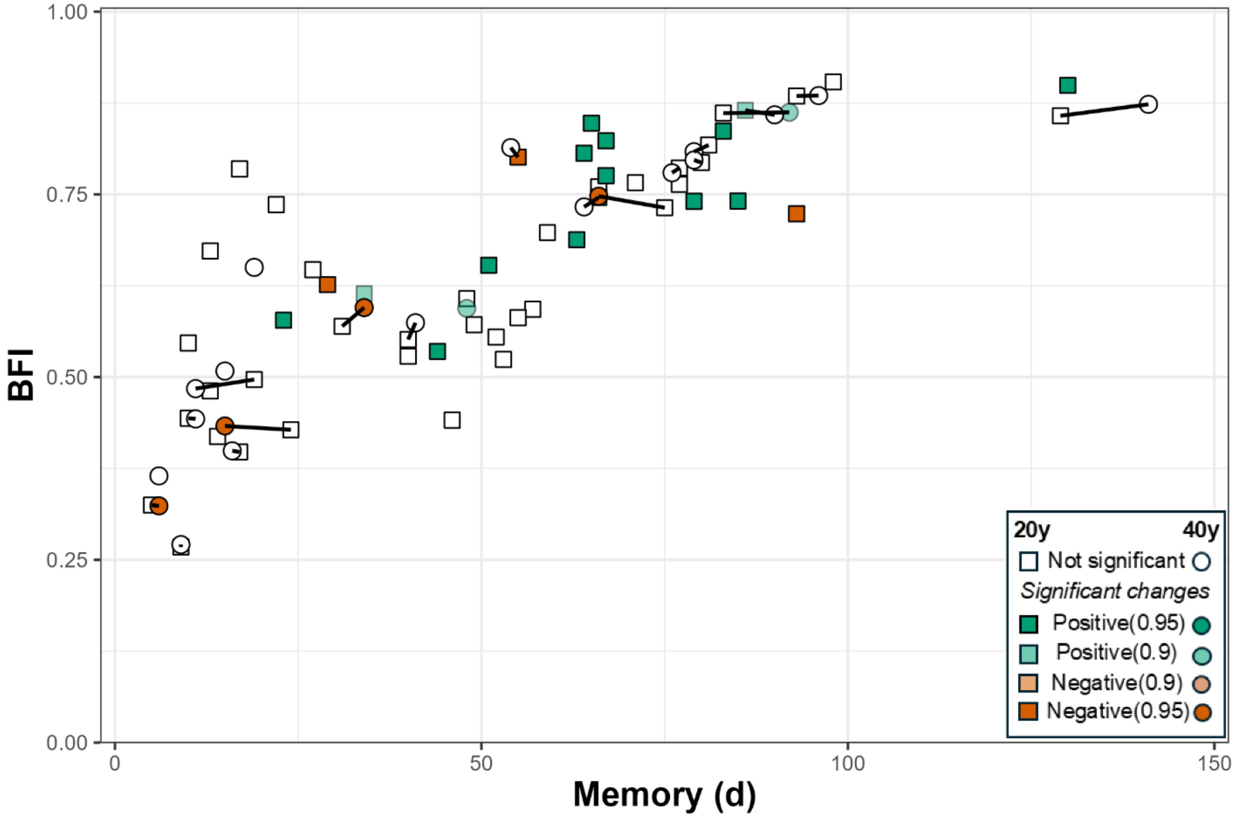


Figure 5: Classification of karst systems based on base flow index (BFI) and memory value. ~~Bold symbols represent the 20-year period,~~ Symbols~~points~~ connected by a line are the same spring.~~ at the two different periods.~~

Figure 5 ~~captures~~ illustrated the diversity ~~variety~~ of European karst systems, ranging from fast-~~-~~responding systems with memory values of only a few days ~~with~~ and a low fraction of slow flow components, to fractured systems characterized by a high fraction of slow flow components and high inertia. Despite this variability, a~~A~~ll springs generally follow one ~~general~~ trend with some deviations ~~alternations~~ at the ~~end~~ extremes of the spectrum. This general trend forms~~is~~ a vertical line from the lower-~~-~~left to the top-~~-~~right corner. Among the fissured systems, in the range of BFI > 0.85, two spring ~~alternate~~ deviate from th~~e~~ise general trend by exhibiting higher memory values. A second ~~alternation~~ deviation ~~can be seen~~is observed among the mature karst systems, where several springs show an increased fraction of slow flow components. Despite the clear~~obvious~~ differences in hydraulic properties, significantly positive and negative trends cover the entire spectrum of springs. However, ~~Only~~ 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 ~~o~~from this~~a~~ continental discharge dataset, it is not possible to directly link hydraulic properties to climate resilience.

4 Discussion

Summarizing the continental trends~~ in hydroclimatic variables~~, it can be stated that ~~trends in ~~air temperature trends are the ~~ones that are ~~most pronounced hydroclimatic changes observed during~~ in~~ both analysed periods. Over the ~~pl~~ast 40 years, air temperature has~~ basically~~ increase~~ds~~ consistently across the ~~in all ~~recharge areas of European karst springs. However, d~~D~~uring the last 20 years, this trend has~~is somehow~~ slowed down in some regions~~areas~~, ~~especially ~~particularly in England. Significant trends in precipitation are ~~rare ~~scarce for both periods. Over the 40-year period, significant precipitation trends are observed only ~~can be detected only ~~locally, and their significance and spatial occurrence ~~further ~~decreases further in~~over~~ the last 20 years.

When c~~C~~onsidering only long-term hydroclimatic trends alone, it becomes challenging to fully attribute changes in discharge from karst areas to hydroclimatic variations~~general trends in observational data over longer periods makes it difficult to explain changes in discharge from karst areas by hydroclimatic changes only~~. This might be due to the influence of ~~the fact that~~ additional factors such as groundwater abstraction, ~~ and other anthropogenic interferences like ~~land cover~~use~~ changes, ~~or ~~and shifts in ~~changes in ~~agricultural -practices, all of which are not accounted for in this analysis. ~~crop rotations in karst areas are not considered ~~Moreover, trends in spring discharge are not solely driven by long-term hydroclimatic changes ~~but also due to the fact that trends in spring discharge might not only be influenced by long-term changes of hydroclimatic conditions but ~~also are also affected by short-term (e.g. seasonal) processes, such as seasonal variations in groundwater recharge and storage dynamics~~changes in processes related to groundwater recharge and storage~~. To better understand these changes, it is necessary to explore potential process changes within specific regional contexts, which follows after a comparison between the general discharge trends with regional variations in river discharge.~~Following a general comparative analysis with river discharge trends, possible process changes will hence be discussed in a regional context.~~

4.1 Comparative analysis with surface water

Due to the relative high abundance of hydrometric stations, numerous~~plenty~~ of trend analysis of river discharge have been conducted both~~ done~~ on continental and local scales. These studies provide a valuable comparison to trends observed in karst areas~~These studies can be used as comparison for the trends in karst areas~~.~~ In fact,~~ On a European scale, river discharge trends ~~on a European scale ~~exhibit ~~show a ~~clear regional pattern closely connected to climatic drivers over recent ~~the last few ~~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 only show a few significant trends (Vicente-Serrano et al., 2019). Conversely, -i~~I~~n southern Europe, regional river discharge trends are spatially negative as a consequence of increasing temperatures and~~ large~~ decline in precipitation (Blöschl et al., 2019; Vicente-Serrano et al., 2019). One exception ~~are ~~is the Pyrenees Mountains, where – on the contrary to karst springs - streamflow trends based on 67 river gauging stations covering the north as well as the south side are largely in~~not ~~significant for the period between 1980 and 2013~~ based on 67 river gauging stations covering the north as well as the~~

south side as concluded by (Clavera-Gispert et al., (2023). Despite the limited Even though the spatial coverage of long-term karst spring data over a long period is comparably low, the results presented in Fig. 2 demonstrate the ability to detect the showed that it is possible to detect the long-term impact of changing hydroclimatic conditions on water resources in karst areas on a continental scale. The general patterns observedpresented for in spring discharge in this study are in linealign with trends in surface runoff, with another key component of the terrestrial hydrological cycle, namely surface runoff.

High flow conditions in the karst system, described by the 10th and 90th percentile, follow the general trends inof monthly discharge over the long period (Fig. 4), consistent with findings from European river systems.. This is again coherent with results of continental studies on European river systems. These regional flood trends show distinct patterns. significance in flood trends show a distinct regional pattern, which is somehow equal to the trends in mean river discharge. 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). Following this pattern, In south-east France, river discharge in south-east France has mainly negative trends are mostly negative (Mangini et al., 2018). Furthermoreand, decreasing flood magnitudes are evidentdiscovered in the southern part of the Alps (Mangini et al., 2018). In the Mediterranean, flood frequency is decreasiesng but while floodthe magnitude trends shows an increaseing trend, both for moderate (95th percentile) and high (99th percentile) floods (Mangini et al., 2018; Tramblay et al., 2019). Additionally, cChanges can also be detected in the characteristics of floods which is most prominent in a considerable increase of medium to large flash flood occurrence in Europe in the 21st century compared to the 1980s (Owen et al., 2018), even though major floods (25 to 100-year return period) show an overall, yet but insignificant, increase (Hodgkins et al., 2017).

The consistency betweenin European flood trends and karstic flows trends indicates that is a sign that groundwater recharge in karst areas follows aligns with the same trend as surface runoff trends on a catchment scale. This suggests A clear sign that global changes in hydroclimatic variables impact both runoff and infiltration components of the water cycle. But we can assume that Tthe concentrated infiltration typical of karstic zones systems likely amplifies may reinforce theise trendspattern, while other aquifer types may experience more buffering effects due to their greater inertia.and that this would probably be buffered for other types of more inertial aquifers.

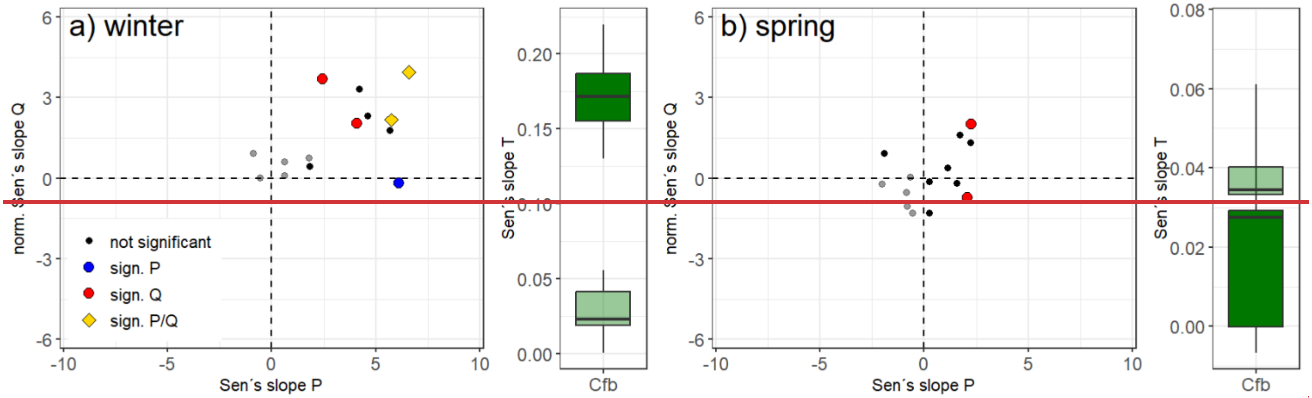
However, the evolution of high and low flow trends between both periods in high and low flow in karst areas over the different periods indicates potential process changes in the lastrecent decades (Fig.4). Over the 40-year period, most of the springs follow roughly a straight line from the lower left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

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 ~~thorough~~ detailed local-scale analysis~~-~~ is beyond the scope of this study~~on a local scale is not focus of the analysis~~, evidence supporting ~~for~~ some of the described discharge trends can be given. According to the results, fall is the seasons ~~of~~ with the highest sensitivity of spring discharge~~ changes~~ to changes of precipitation. (Fig. 3). A ~~likely~~ plausible explanation ~~would be~~involves the combination of two phenomenon ~~leading to severe~~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 regions specific areas with consistent spatial trends.

Over the last 40 years, discharge has decreased in the S~~s~~prings Lison and Verneau~~n~~, both situated in the same part of the Jura Mountain and characterized ~~two springs with~~by long-term discharge records ~~time series~~ (40 years)~~ located in the same part of the Jura Mountain~~. Looking at the general trends in the area (Fig. 6), temperature, and ~~therefore~~ consequently evapotranspiration, has increased ~~in~~ across all seasons over the last 40 years.~~,~~ This, combined with significantly decreasing fall precipitation contributes to lower discharge in fall.~~resulting together with significantly decreasing fall precipitation for the entire region in lower discharge in fall.~~ In the entire region, the distribution of precipitation shifted, with~~changes to~~ more precipitation in winter and spring ~~and~~ but less during the other two seasons. Over 40 years, the partly significant decrease in fall precipitation might explain the local precipitation decreases in the area (Fig. 2d).

During the last 20 years, precipitation ~~during~~ in spring and, ~~especially~~ particularly, winter has increased~~s~~ significantly, which might explain the absences of consistent ~~overall~~ negative discharge trends during this period. Additional to the precipitation increase in winter, winter air temperature has also increased, ~~during winter with a high~~ accelerating over~~on during~~ the last 20 years. ~~Considering~~ In~~the~~ mountainous regions~~environment~~, this likely results in reduced~~a decrease in~~ snow contribution, ~~especially during the last 20 years can be assumed in coherence with previous studies showing~~ a pattern supported by earlier studies reporting a significant decrease in snow precipitations in the north part of Jura Mountains (Charlier et al., 2022). ~~Therefore~~In summary, ~~it can be summarized that~~ long-term changes in the Jura Mountain are mainly related to ~~increases in~~rising temperature, ~~influencing~~ affecting snow contribution during~~in the~~ cold seasons and increasing evapotranspiration during~~ the~~ warm seasons. Both effects ~~related to increasing temperature~~ have been highlighted in previous studies of karst systems in temperate climates (Fan et al., 2023) ~~but also~~and mountainous regions ~~in~~ with Mediterranean climates (Lorenzi et al., 2022). However, in the case of Jura mountains, these changes~~is~~ do~~es~~ not result in ~~lead to~~ overall regional-wide decreasing discharge. A likely ~~possible~~ explanation is that increased evapotranspiration is offset~~compensated~~ by higher precipitation in cold ~~-~~seasons ~~precipitation~~ over~~during~~ the p~~l~~ast 20 years, a process ~~already~~ previous discussed for ~~a case study in~~ south~~-~~western England (Brenner et al., 2018).



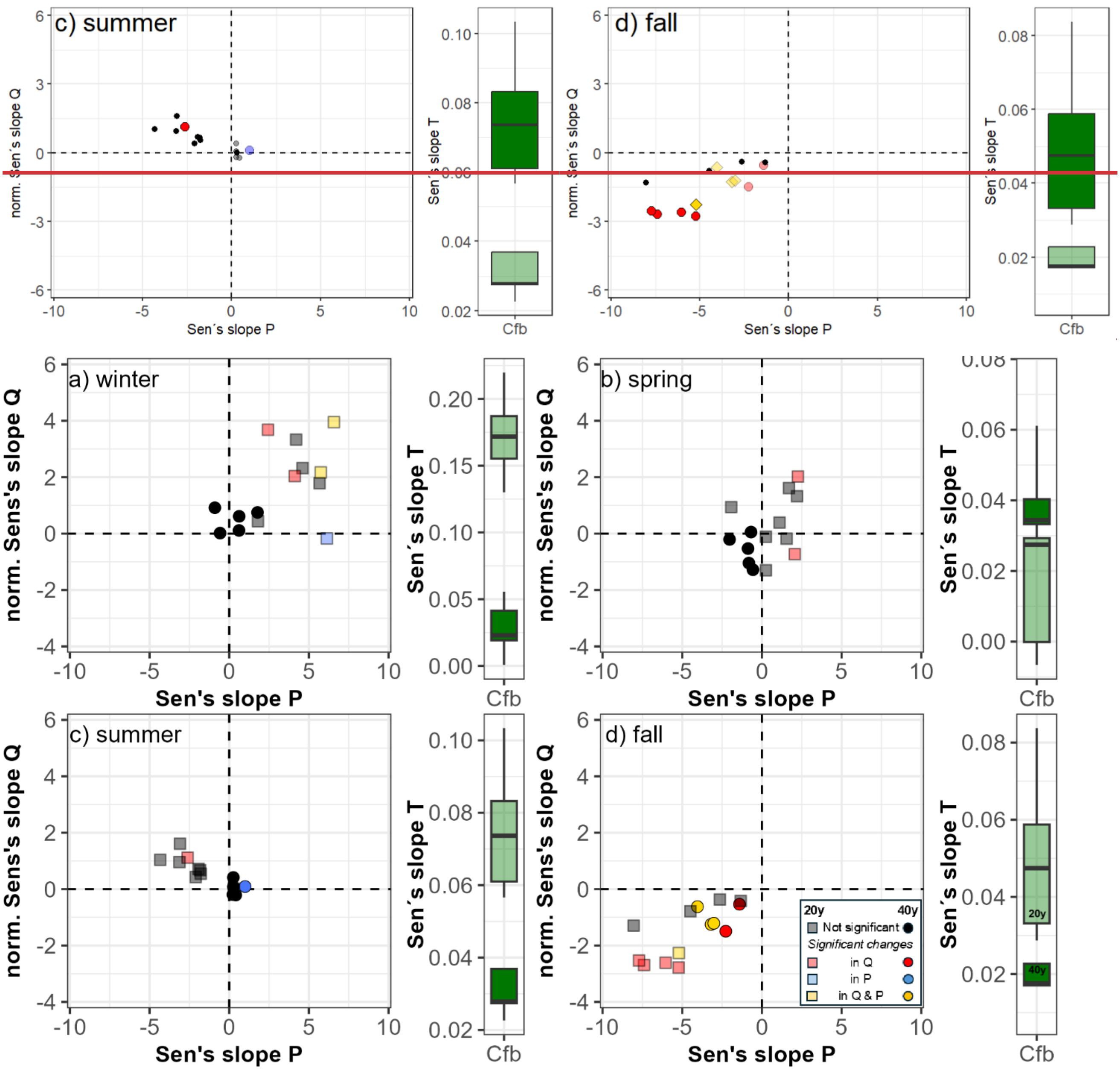
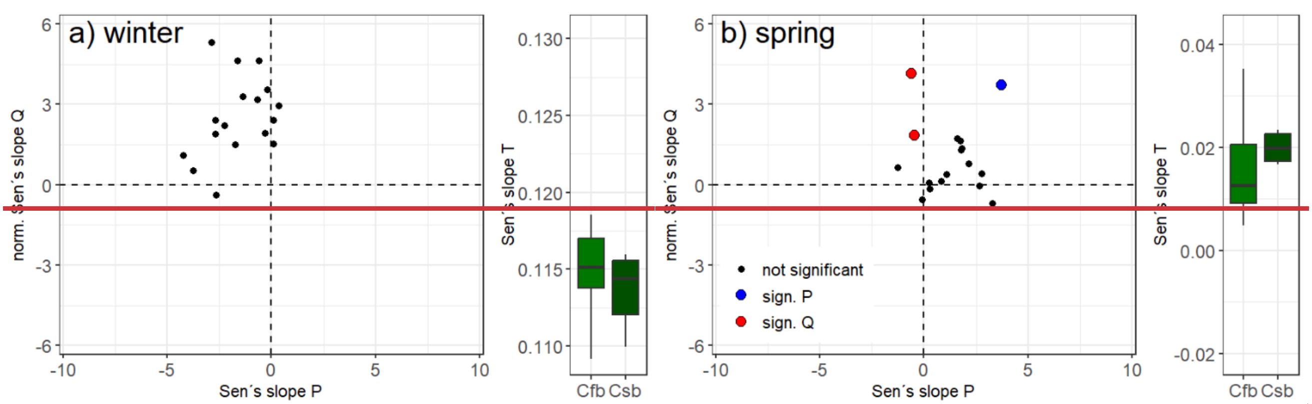


Figure 6: Comparison of changes in precipitation and discharge trends for a) winter, b) spring, c) summer, and d) fall in combination with temperature (boxplot) for all springs located in the Jura mountains (France). Springs indicated by red dots have significant changes in discharge, by blue dots in precipitations and diamonds have significant changes in both seasonal precipitation and discharge. ~~Bold symbols represent the 20-year period.~~The line in the boxplot represents the median.

The Grand Causses region is of particular~~specific~~ interest due to its location along a climate zone boundary. Previous ~~analysis~~ studies have highlighted that such ~~those~~ areas, especially those affected by changes in snow contributions,~~or areas with changes in snow contribution~~ are ~~prone~~ susceptible to variations in ~~for changes in~~ river discharge (Berghuijs et al., 2014) and groundwater level variability (Nygren et al., 2020; Nygren et al., 2021). The climate boundary in the Grand Causses region is connected to elevation differences, dividing the lower parts with Mediterranean climate from the parts with higher elevation (temperate climate). ~~Summarizing~~ Based on the results from Fig~~.~~ure 2~~b)~~, several springs in the region show positive discharge trends over~~for~~ the p~~l~~ast 20 years. However, precipitation increases mainly in spring and has a clear negative trend in fall and winter for both climate zones (Fig.7), ~~in link with~~connected to a lower occurrence of Mediterranean storm events – which~~that~~ historically occurred in fall season - in the last decades. The ~~highest number of~~most significant discharge changes ~~in discharge occurs~~ are observed in summer, all of them positive. Similar to the Jura mountains, air temperatures have increased across~~in~~ all seasons, most pronounces in winter. Despite the decrease in winter precipitation, spring discharge shows an increase~~s~~, albeit not ~~even though not~~ significant~~ly~~. This regional discharge trends indicate increases ~~in discharge can be seen~~ in all seasons except ~~from~~ fall. This ~~last point is coherent~~aligns with reduced~~the decrease of~~ precipitation~~,~~ and, ~~thus~~ consequently, decreased ~~of~~ recharge during the fall season. One potential~~A possible~~ explanation for the ~~resulting in~~ overall ~~increasing~~ discharge increases~~,~~ could ~~might~~ be a ~~s~~substantial~~trong~~ reduction in snow contribution.~~, l~~ This, combined with higher spring precipitation, likely leads to system saturation. Despite the elevated temperatures in the warmer seasons, the increased recharge supports greater discharge levels, persisting until the fall season.~~eading together with increased spring precipitation to a total saturation of the systems. Despite increased temperatures in the warm seasons, this leads to increase discharge until fall.~~



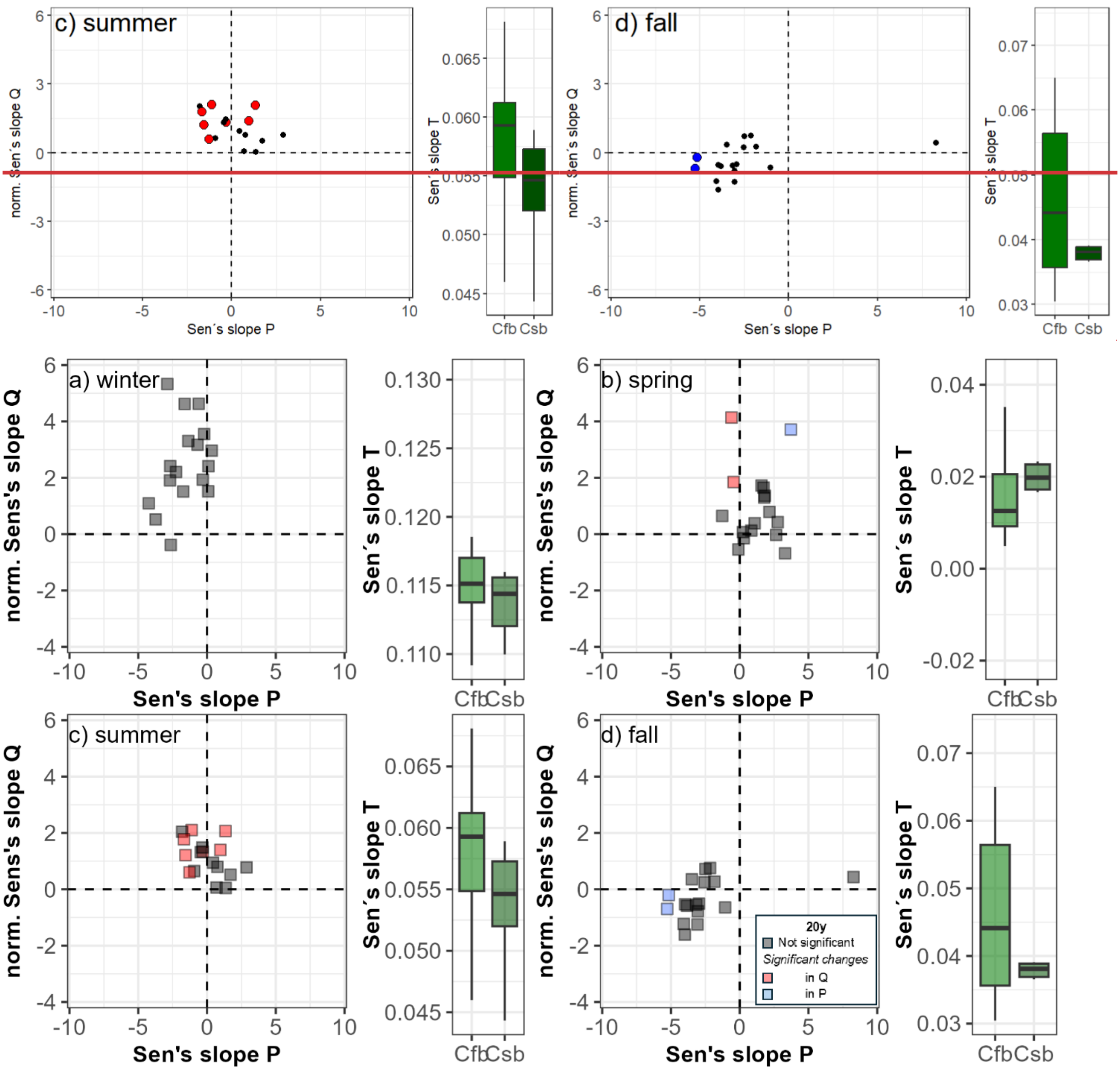


Figure 7: Comparison of changes in precipitation and discharge trends for a) winter, b) spring, c) summer, and d) fall in combination with temperature (boxplot) for all springs located in the Grand Causses region (France). Springs indicated by red dots have significant changes in discharge, by blue dots in precipitations and diamonds have significant changes in both seasonal precipitation and discharge. The line in the boxplot represents the median.

4.3 Additional forcings impacting-karst water resources

Building on the analysis of ~~Following the reasoning for the two French karst areas of~~ the Jura Mountains and Grands Causses region~~ in the previous section~~, it can be concluded that, in absence of significant precipitation changes, temperature is the primary~~the main~~ driver of climate change related trends in European karst discharge. Anthropogenic warming is closely ~~connected~~ linked to increased evapotranspiration, which affects ~~. This has an impact on~~ 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).

~~Another factor influencing evapotranspiration is~~ C~~c~~hanges in land use or land cover also play a critical role in changes of evapotranspiration. Several studies have highlighted the influence of land use changes on trends in river discharge (e.g. Vicente-Serrano et al., 2019) and extreme events, especially the spatial and temporal occurrence and severity of drought events (e.g. Brunner and Stahl, 2023). Even short-term changes due to crop rotations in agricultural areas ~~have a~~ directly affect~~impact on~~ groundwater storage (e.g. Dakhlalla et al., 2016). ~~Globally~~On a global scale, almost 5% of karst regions experienced land use or land cover changes ~~in karst areas could be detected for almost 5% of the surface for the period~~ between 1992 and 2020, predominantly due to ~~most of them related to~~ agricultural reclamation or reforestation (Zhang et al., 2023). However, analysing t~~T~~he impact of these changes on a larger scale is challenging due to lack of ~~difficult to analyse on a larger scale since~~ fundamental research on percolation and recharge processes is karst areas~~ is lacking~~, ~~especially~~ particularly those ~~for those~~ covered by forest (Vilhar et al., 2022).

Possible explanations for the increase in discharge or ~~moderation~~ moderated ~~of~~ downward trends - not only in the Grands Causses region - can also be found in the dependency of spring discharge on large-scale atmospheric circulations, as seen in Italian karst areas (e.g. Fiorillo et al., 2021). ~~Sudden~~ Abrupt changes or even breaks in the system behaviour during the p~~l~~ast decades ~~can also be detected in~~are evident in other compartments of the hydrological cycle, driven by~~. These are closely connected to~~ fluctuations in~~of~~ large-scale atmospheric circulations~~,~~. These circulations impact hydroclimatic variables such as wind speed, temperature, and precipitation across Europe ~~which drive different hydroclimatic conditions (e.g. wind speed, temperature, precipitation) over Europe~~ (e.g. Ionita et al., 2022; Deng et al., 2022). For European river basins, the 1980s ~~highlight~~ marked a point ~~starting point~~ where periodic changes in river discharge became closely linked ~~connected~~ to large-scale atmospheric circulations, e.g. the North Atlantic Oscillation (NAO),~~ occur~~ for the first time (Lorenzo-Lacruz et al., 2022). This transient connection between periodical fluctuations in European river discharge and large-scale atmospheric circulations can be detected on both continental (e.g. Lorenzo-Lacruz et al., 2022) and regional scales (e.g. Giuntoli et al., 2013; Boé and Habets, 2014)~~ scales~~. Furthermore, ~~the~~ atmospheric circulations impact ~~has an impact on~~ long-term groundwater level variability (e.g. Holman et al., 2011; Neves et al., 2019; Rust et al., 2018; Rust et al., 2019, Baulon et al., 2022). These periodic signals propagate through processes~~via recharge to the aquifer~~ and account on average for 40 to 55 % of groundwater level variability and therefore play an as important role as current climate conditions (Neves et al., 2019; Rust et al., 2019).

5 Conclusion

Observational data from European karst areas were analysed for two different period. The first period (1982- 2021) focuses on European springs with the longest available time series, while ~~and~~ the second one covers the last two decades. The~~is~~ shorter period was ~~chosen~~ selected to identify~~ any possible~~ potential acceleration or moderation of trends on a regional scale. By a~~A~~nalysing trends in observational hydroclimatic and hydrological variables over the last 20 years provide, this study provides ~~a~~ continental insight into these changes and at the same time allow for a higher number of karst springs representing diverse ~~to cover a wide range of~~ hydraulic properties, climates, and topographies.

Although hydrological properties of karst systems ~~differ widely~~vary significantly, the results highlight the independence~~y~~ of long-term discharge trends ~~in discharge~~ from the maturity or degree of karstification. Both~~,~~ systems dominated by ~~with a dominant~~ fast flow components ~~as well as~~and those with predominant ~~systems with a dominant~~ base flow components show significant increasing and decreasing discharge trends, respectively. ~~Out~~ O~~o~~f the two investigated hydroclimatic variables, temperature increases played a pivotal role in explaining the observed trends. Conversely, changes in precipitation, including seasonal variations, were insufficient to account for the detected discharge trends.~~the increase in temperature played a major role in the explanation of the discovered trends. The impact of changes in precipitation, including seasonal changes, is not able to explain the detected changes in discharge.~~ The analysis of observation data inherently simplifies the complex groundwater recharge and flow processes in karst areas to a degree that system changes cannot be detected. As ~~mentioned~~highlighted, the list of possible drivers of such changes is ~~long~~ extensive, so only a few of them were highlighted here. One important group are changing climatic conditions which can be divided into cyclic changes, due to large-scale atmospheric circulations, and continuous changes related to the timing and intensity of precipitation and temperature changes during short-term periods, e.g. seasons. These dynamics can~~types of changes can~~ be better addressed through ~~considered by~~ process-based groundwater recharge model approaches. Utilizing such models to ~~Applying these types of models and~~ analyse~~ing~~ discharge changes in ~~discharge from~~ karst areas, with their unique hydrologic properties, ~~might~~may help overcome challenges associated with~~the disadvantage related to the validation of those~~ model validation~~s~~.

However, the here presented results have a practical implication~~relevance~~ for modelling discharge in karst areas. Most time-series are ~~rather~~ relatively short, which increases ~~bears~~ the risk of basing analyses on periods influenced ~~using periods which are affected~~ by changing climate conditions without taking account the associated shifts. Moreover, developing numerical models and validating them using trend-affected time series—without accounting for the underlying drivers or evolving processes—risks producing misleading future predictions of spring discharge by assuming continuous linear trends.~~Building up numerical models and validate them on trend-effected time series without considering the drivers or changing processescause high risk of misleading future predictions of spring discharge.~~ ~~This also includes short-term fluctuations in climatic drivers, e.g. caused by large-scale atmospheric circulation.~~

Author contribution

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 & editing: MG, JBC, YC, AH

Competing interests

The authors declare that they have no conflict of interest.

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