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High-Resolution Karst Spring Discharge Datasets of the Euro-Mediterranean Mountain Regions

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Abstract. Karst groundwater systems exhibit heterogeneity in recharge, circulation, and discharge, occupying a unique position within groundwater systems. This complexity facilitates rapid responses via the preferential flow routes, making karst systems vulnerable to climatic and anthropogenic pressures. High-altitude karst aquifers are particularly susceptible to shifting climate patterns—specifically rising temperatures, declining snow cover, and increasingly less and inconsistent precipitation—within the Mediterranean climate hotspot. Effective sustainable management of these groundwater systems require robust hydrological modelling; however, the application of such models is often constrained by the availability of high-quality, reliable datasets. This study presents a comprehensive collection of high-resolution karst spring discharge data from major Euro-Mediterranean mountain belts, including the Atlas, Betics, Pyrenees, Jura, Alps, Carpathians, Apennines, Dinarides, Hellenides, Balkans, Taurus, Levant, and Zagros. We compiled a total of 118 discharge time series specifically curated for hydrological modelling. Geographically, the dataset is led by the Alps (approx. 42%), followed by the Dinarides (approx. 10%), with the Apennines, Carpathians, and Zagros each contributing approx. 7%. The Levant and Taurus account for approx. 5% each, while the remaining regions (Atlas, Balkans, Betics, Hellenides, Jura, and Pyrenees) represent less than 5% each. In terms of temporal resolution, 92% of the records are daily, while hourly and monthly data each comprise 4%. The average record length is 19 years, which is led by a 99-year series from Unica Spring, Slovenia (1926–2025). Regional analysis indicates that the Alps, Apennines, Balkans, Betics, Dinarides, Jura, and Levant maintain average record lengths exceeding 20 years, whereas the Atlas, Carpathians, Taurus, and Zagros range between 10 and 20 years. The shortest average records were observed in the Hellenides and Pyrenees (7 and 8 years, respectively), which is still adequate for hydrological modelling applications.

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1 Introduction

Karst groundwater systems are defined by spatial and temporal heterogeneity, a direct consequence of the complex evolution of secondary (fracture) and tertiary (conduit) porosity (Ford & Williams, 2007; De Waele & Gutiérrez, 2022). The presence of high-conductivity conduit networks integrated within a lower-permeability fissured matrix creates unique hydraulic behaviour that is exceptionally sensitive to both quantitative and qualitative environmental perturbations. Due to these anisotropic flow behaviour, karst aquifers often respond nearly instantaneously to surface conditions, rendering them significantly more vulnerable to contamination (Hartmann et al., 2021; Çallı et al., 2025) and over-extraction (Ladouche et al., 2014; Charlier et al., 2015) than porous or fractured aquifers.

In the era of climate change, a recent analysis of long-term data from European karst spring discharge suggest that increased evapotranspiration, changes in snow contribution, and shifts in seasonal precipitation distribution, intensity and frequency in storm events alter the flow regimes of karst systems (Giese et al., 2025). In that frame, mountainous karst aquifers represent some of the most sensitive hydrogeological indicators, particularly within the Mediterranean climate hotspot (Diffenbaugh & Giorgi, 2012; Jódar et al., 2021). These high-elevation systems serve as "water towers", not only providing essential water supplies to lowland regions but also sustains the karst groundwater dependent ecosystems (Viviroli et al., 2007; Siegel et al., 2023). However, the Mediterranean’s unique climatic position makes it susceptible to shifting atmospheric circulation patterns, which directly threaten the recharge mechanisms of these vital groundwater reservoirs (Giorgi & Lionello, 2008). Central to this vulnerability is the observed shift in cryospheric dynamics across Euro-Mediterranean mountain belts (Notarnicola, 2020). Recent climate studies have documented a systematic decline in total snow cover, reduced snow duration, and intensified spring-season melt rates (Hock et al., 2019; Matiu et al., 2021; Notarnicola, 2022). As snowmelt-dominated recharge is increasingly replaced by rain-on-snow events or immediate runoff, the temporal distribution of karst spring discharge is shifting (Vremec et al., 2025). This often results in diminished summer baseflows and compromised water security for downstream populations dependent on these sources (Xanke & Liesch, 2022). These hydrological changes are further compounded by other environmental factors, including land-use changes and vegetation cover modifications, which can alter infiltration, recharge patterns, and spring response (Kovačič et al., 2020; Ravbar et al., 2024).

To accurately predict the future of these resources, many hydrogeologists have emphasized the urgent need for robust hydrological models capable of simulating non-linear karst dynamics. Whether employing machine learning architectures or physically-based distributed models, the reliability of recharge and discharge simulations is linked to the availability of high-resolution, continuous observational data (Ortenzi et al., 2026). Sub-daily or daily discharge time series are a prerequisite for capturing the "flashy" hydrological response of many karst systems, especially for the extreme-event predictions, which are often obscured by coarser, monthly datasets (Çallı, 2026). The karst hydrogeologists community has successfully led a sequence of initiatives to address these challenges. This began with the World Karst Aquifer Mapping Project (i.e. WoKAM) (Chen et al., 2017), which established the first global distribution of karst aquifers, followed by the World Karst Spring Discharge Dataset (WoKaS) (Olarinoye et al., 2020) and the Global Isotope database as the follow-up WoKaS-Iso (Zang et al., 2026), which aimed to compile a worldwide data catalogue for a better understanding and management of karst aquifers. Regional efforts were further refined by the Mediterranean Karst Aquifer Map (i.e. MEDKAM) (Xanke et al., 2024), providing detailed spatial data for the Mediterranean and the Alps (Goldscheider et al., 2025). Most recently, the Most Important Karst Aquifer Springs (i.e. MIKAS) project (Stevanović, 2023) focused on identifying key global springs for improved management. Building upon this foundation, the Karst

Mountains of Euro Mediterranean, Modeling, Analysis and Network (i.e. KaMERaMAN) initiative was launched at the Eurokarst Symposium in Rome, 2024 (Çallı et al., 2024). KaMERaMAN specifically targets the collection of a high-resolution, quality-checked, and without (or negligible)-gap discharge dataset for the mountainous karst springs of the Euro-Mediterranean region, specifically tailored for advanced hydrological modelling.

Despite these efforts to aggregate global data, existing repositories frequently fall short of the requirements for high-resolution hydrological modelling in karst springs. Previous initiatives have often relied on more heterogeneous records by the mixture of daily to annually temporal resolution discharge data (Olarinoye et al., 2019). Even though the researchers classified the dataset into quality clusters (considering the length, temporal resolution, and existing gaps), the high-quality labelled datasets still lack long continuity, and the majority of those dataset seems not adequate for a proper hydrological modelling experiment. These inconsistencies introduce substantial uncertainty into hydrogeological assessments, limiting the ability of researchers to calibrate complex models across diverse geomorphological settings. Addressing this critical data scarcity, the present study introduces a comprehensive, high-resolution discharge database specifically targeting Euro-Mediterranean mountainous karst springs under the KaMERaMAN framework. Within this database, total of 118 mountainous karst spring discharge data was gathered from 13 different mountain regions in the Euro-Mediterranean (Atlas, Betics, Pyrenees, Jura, Alps, Apennines, Dinarides, Carpathians, Balkans, Hellenides, Taurus, Levant, and Zagros). Among all, Alps (Austria, France, Slovenia, and Germany) consisting of 50 karst springs (42% of the total dataset) is the top-represented, and Atlas (Morocco and Algeria) consisting of only 2 karst springs (1.6% of the total dataset) is the least-represented mountain region. The other mountain regions are almost equally-represented within the dataset (between 5-10%). By integrating national archives, digitized historical reports, and institutional collaborations, we have curated a dataset characterized by enhanced continuity and rigorous quality control. This contribution provides an open-access foundation for the next generation of karst research, enabling more precise climate impact assessments and sustainable water management strategies in one of the world's most water-stressed regions.

2 Methods

2.1 Selection of the Karst Springs

The selection of karst springs followed a multi-step and iterative screening procedure. First, we conducted an in-depth assessment of the MEDKAM database to identify named karst springs located within the major karst mountain belts of the Euro-Mediterranean region. These springs were then cross-checked inside existing inventories, particularly the World Karst Spring (WoKaS) database, from which discharge and metadata were accessed where available. Subsequently, we extended the initial inventory through a systematic review of the scientific literature and targeted web searches to identify additional karst springs not included in WoKaS. In parallel, we explored the web platforms of national hydro-meteorological institutions to obtain directly downloadable discharge records for karst springs. In addition, karst spring discharge datasets that were directly shared in digital format by institutions or collaborators were incorporated into the database. For several springs recommended by collaborators, discharge records available only in report form were retrieved and digitized from published PDF documents (or printed reports). To further broaden the candidate pool, national stream-gauging station databases were also screened, focusing on stations located in karstic mountain regions. Each candidate stream-gauging station was manually inspected using topographic and hydrographic information, and only those with minimal upstream surface drainage—thus representative of predominantly karstic discharge—were retained. The resulting candidate spring list, together with its associated metadata, was then shared with regional collaborators (the co-authors of this paper) for expert evaluation. Based on this collective assessment, unsuitable sites were removed from the database. The final dataset of karst springs was obtained after this collaborative refinement process (Fig 1).

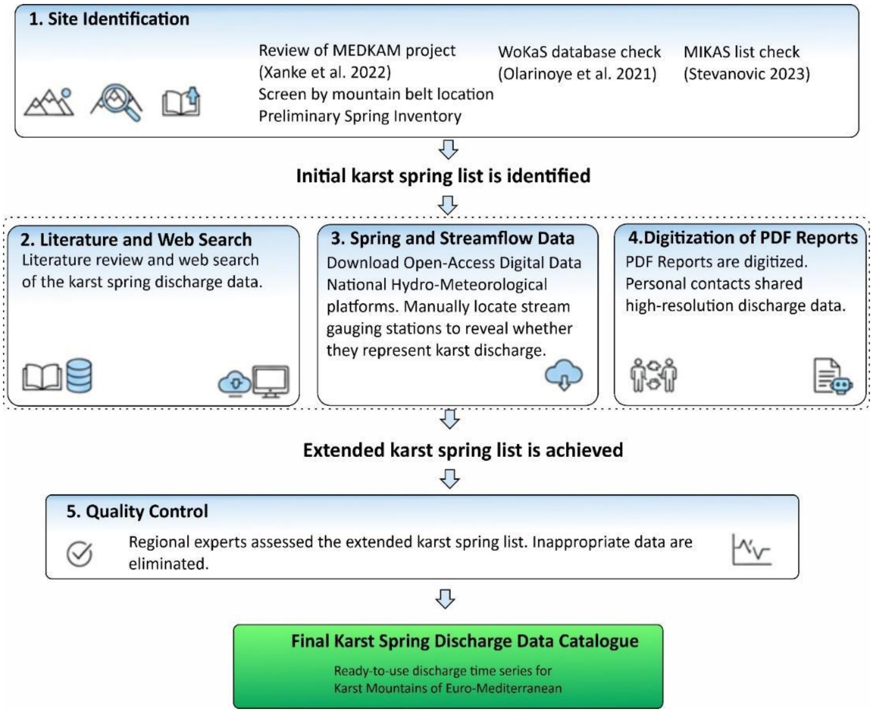

Figure 1: Data collection workflow strategy

2.2 Multi-Source Data Acquisition

The karst spring discharge data within the study is gathered via several sources. They are (i) directly download of the open-access digital karst spring discharge data from national hydrometeorological services and regional environmental agencies, (ii) download and digitization of the open-access PDF annual reports from the national hydrometeorological services, (iii) shared digital discharge data by the colleagues and (iv) discharge data from academic works as unpublished theses and published articles. In Table 1 the data sources are shared in which direct download of the digital karst spring discharge is possible.

Table 1. The direct download of the digital discharge data: Automated scraping or manual harvesting from national hydro-meteorological portals

Country	**Data Access Link**	**Quality check**
Austria	Bundesministerium für Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasserwirtschaft (Federal Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management) (www.ehyd.gv.at)	J Eybl

France	SNO KARST (Karst Observatory Network) (https://sokarst.org/en/data/) Eaufrance Hydroportail (Hydrological Portal of France) (https://hydro.eaufrance.fr/)	H Jourde N Mazzilli B Arfib S Beranger J-B Charlier M Steinmann
Italy	Sistema Informativo Regionale Meteo-Idro-Pluviometrico (Marche Regional Meteorological-Hydrological Information System) (http://app.protezionecivile.marche.it/sol/contatti.sol?lang=it) ARPA Umbria (Regional Hydrological Service of Umbria) (https://apps.arpa.umbria.it/acqua/contenuto/portata-delle-Sorgenti) WoKaS (https://github.com/iGW-TU-Dresden/WoKas)	C Massari, L Di Matteo, D Valigi, D Fronzi, M Dionigi
Germany	Bayerisches Landesamt für Umwelt (Bavarian Water Management Service) (https://www.gkd.bayern.de/en/groundwater/flow-of-springs/tables)	SS Çallı
Slovenia	Agencija Republike Slovenije za okolje (Slovenian Republic Water Agency) (https://vode.arso.gov.si/hidarhiv/pov_arhiv_tab.php)	N Ravbar, C Mayaud
Croatia	DHMZ - Državni hidrometeorološki zavod (Croatian Hydrometeorological Service) (https://hidro.dhz.hr/)	SS Çallı, C Mayaud, N Ravbar
Czechia	Cesky hydrometeorologicky ustav (CHMU) (Czech Hydrometeorological Service) (https://isvs.chmi.cz/ords/f?p=11002:2:113580288468140:::RP,2:P2_SEQ:%5C759%5C)	P Pracný
Israel	Israeli Government Water and Sewerage Authority (https://data.gov.il/he/datasets/water_authority/spring_discharge)	A Burg
Syria Lebanon Greece Serbia Iraq Iran	WoKaS (https://github.com/iGW-TU-Dresden/WoKaS)	Olarinoye et al. (2019)

In Table 2, the karst spring discharge data are downloaded as PDF files by using the shared links, then digitized by the team members. The appropriate karst spring names and coordinates are determined by the guide of the national experts, and the available literature. Many of the scanned discharge annual reports exhibit the annual hydrograph of the selected spring, which helped us to visually compare the digitized data hydrograph for validation. The visual comparison-check proved that all the digitized discharge data are correctly digitized without any significant uncertainty.

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Table 2. Downloaded and digitized annual reports (scanned PDF files)

Country	Data Access Link	Quality check
Slovakia	Slovensky Hydrometeorologicky Ustav (Slovakian Hydrometeorological Service) (https://www.shmu.sk/sk/?page=2649)	P Malik
Bosnia and Herzegovina	Federalni Hidrometeoroloski Zavod (Bosnian Federal Hydrometeorological Service) HIDROLOŠKI GODIŠNJAK, https://www.fhmzbih.gov.ba/latinica/HIDRO/godisnjaci.php#	SS Çallı
Türkiye	Devlet Su İşleri (Turkish State Hydraulic Works) (www.dsi.gov.tr)	SS Çallı

Table 3 shows the details of the karst springs which are directly shared by the collaborators. Those discharge data are shared as digital files, and only tidied up by the first author.

Table 3. Institutional Collaboration: Data shared by the regional experts

Country	Spring Name	Data provider, Quality Check	Institution
Albania	Selita Blue Eye (Syri-i Kalter)	R Eftimi	Independent researcher
Algeria	Ain Youkous	F Chemseddine	University of Tebessa
Morocco	Ras El Ma (Taza, Middle Atlas)	B Akdim	Université Privée de Fès (Naoura et al. 2021)
Italy	Ussita	C Massari, M Dionigi	Consiglio Nazionale delle Ricerche (CNR)
Spain	Garces Fuente Alta Natividad	J Jódar	IGME-CSIC
Türkiye	Pınarbaşı	M Çelik	Ankara University
France	La Loue	J-B Charlier	French Geological Survey (BRGM)
Bulgaria	Yazo Kyoshka	A Benderev	Bulgarian Academy of Sciences
	Vrisa Beden Mugla	M Deliyska	Bulgarian Academy of Sciences

2.3. Dataset Repository Organization and Labelling

The downloadable repository is structured to facilitate transparent reuse and straightforward navigation of the dataset. The root directory contains: (i) a master metadata table (in .csv format) compiling the full inventory of springs and their attributes (geographic coordinates, elevation, monitoring period, data source, and references); (ii) individual time-series data files of the karst springs which are grouped by the region; (iii) a README document describing file structure, variable definitions, units, and data provenance; and (iv) supplementary documentation (e.g., methodological notes and source acknowledgements) to ensure traceability and reproducibility. This hierarchical organization allows users to quickly identify stations of interest while maintaining a consistent link between raw discharge records and their descriptive metadata.

Data files are labelled using a standardized naming convention designed to encode essential geographic and administrative information directly in the filename. Each record is identified by a four-part code:

[Mountain Range]_[Station Number]_[Country ISO Code]@[Spring Name]

Mountain Range (3-letter code): Indicates the orographic region (e.g., ALP = Alps, PYR = Pyrenees, CAR = Carpathians). Station Number (01–99): Sequential identifier within each mountain range. Country ISO Code (2 letters): Country where the spring is located (e.g., AT = Austria, SI = Slovenia, TR = Türkiye, FR = France, DE = Germany, ES = Spain). Spring Name: Original name of the karst spring, retained to preserve consistency with national datasets and literature.

Springs are grouped primarily by mountain belt rather than political boundaries, reflecting the hydrogeological continuity of karst systems that often extend across multiple countries. Consequently, station numbering continues sequentially within the same mountain range even when the country changes. For example, in the Alpine dataset, the first 44 springs belong to Austria, followed by springs located in France, Slovenia, and Germany:

ALP_01_AT@Aubachquelle … ALP_44_AT@Widumbachquelle, ALP_45_FR@Gillardes, ALP_46_SI@Kamniska Bistrica, ... ALP_50_DE@Bergmannsquellen.

A similar structure is applied to other regions, such as the Pyrenees: PYR_01_ES@Garces, PYR_02_FR@Fontestorbes.

This convention ensures that filenames remain both human-readable and machine-actionable, enabling efficient filtering, automated processing, and unambiguous regional association across transboundary karst environments.

2.4 Spatiotemporal Coverage of the Dataset

The compiled karst spring discharge dataset spans a wide range of Euro-Mediterranean mountain belts formed during the Alpine orogeny, covering pronounced latitudinal, climatic, and environmental gradients (Fig. 2). Spatially, the springs extend from humid, high-latitude and high-elevation regions of central and western Europe to semi-arid Mediterranean and eastern mountain belts, encompassing strong contrasts in precipitation regime, snow persistence, vegetation cover, and recharge seasonality. Overall, the database consisting of 118 karst springs throughout the Euro-Mediterranean karst mountain region. This spatial diversity captures karst systems ranging from snow-dominated alpine catchments to rainfall-controlled Mediterranean and transitional environments. Alp mountains are placed a very important position in the dataset which is led by the Alps (approx. 42%), followed by the Dinarides (10%), with the Apennines, Carpathians, and Zagros each contributing 7%. The Levant and Taurus account for 5% each, while the remaining regions (Atlas, Balkans, Betics, Hellenides, Jura, and Pyrenees) represent less than 5% each. In terms of temporal resolution, 92% of the records are daily, while hourly and monthly data each comprise 4%. Temporally, the dataset comprises discharge time series of variable record length. The average record length is 19 years, which is led by a 99-year series from Unica Spring, Slovenia (1926–2025) (Fig. 3). In order to minimize geographical gaps, multi-year monitoring periods and monthly observations are also included to the dataset, as well (Fig. 3), particularly in data scarce regions (Fig. 4**).** Together, this spatiotemporal structure provides a coherent yet diverse representation of karst spring discharge variability across climatically and ecologically distinct mountain settings within a broadly comparable orogenic framework.

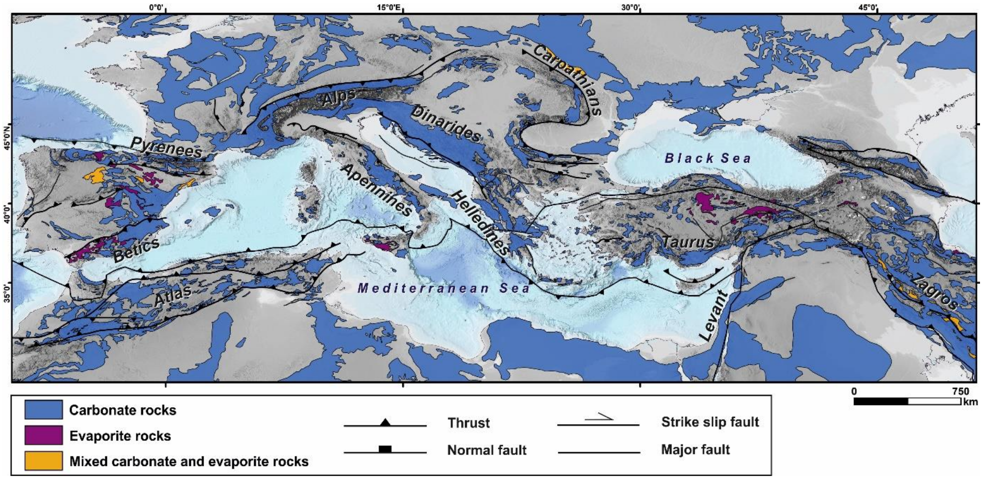

Figure 2: Euro-Mediterranean karst mountain regions being investigated within the study. Karstifiable rocks derived from WoKAM (Chen et al., 2017).

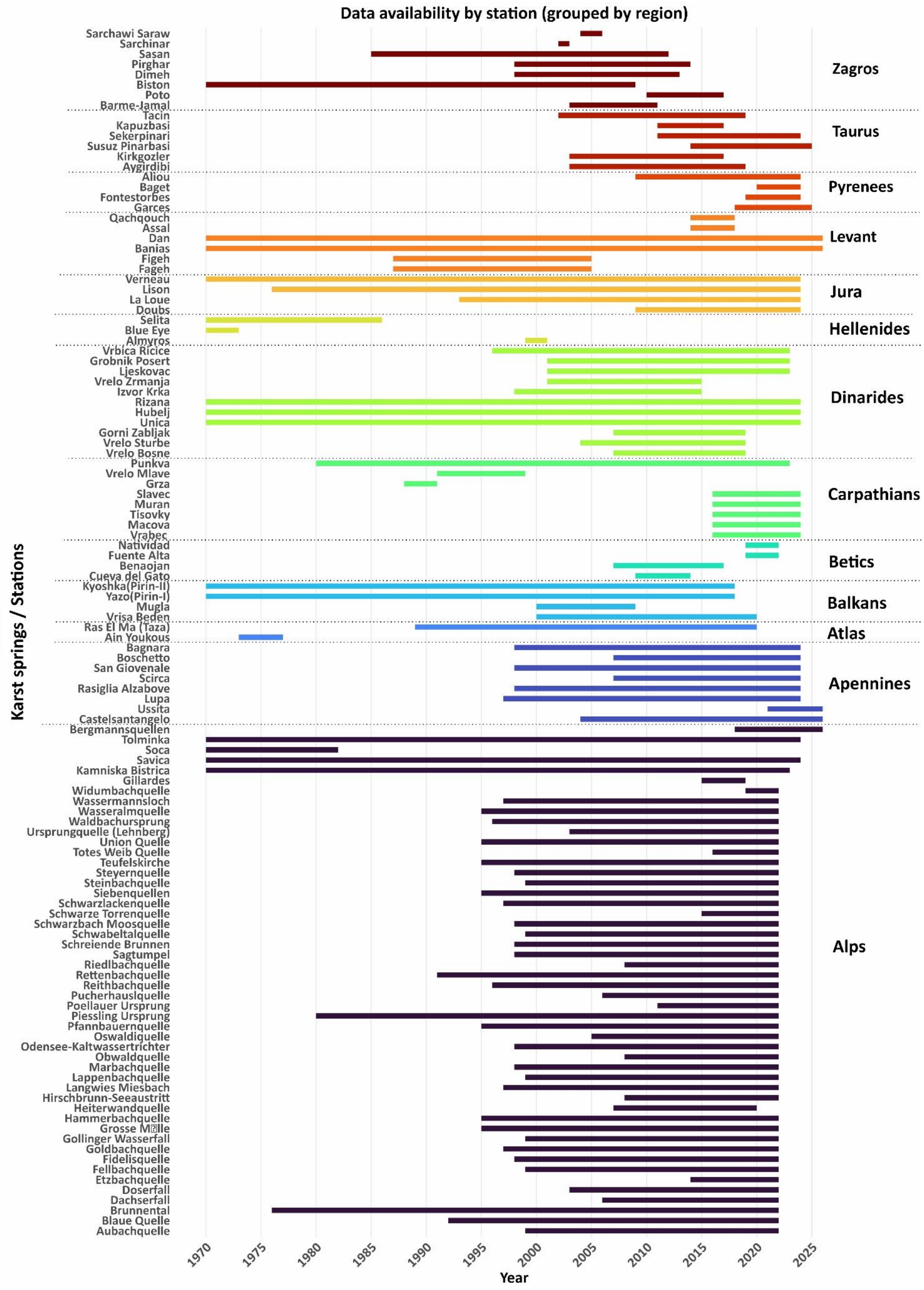

Figure 3: Temporal coverage of the karst springs discharge dataset

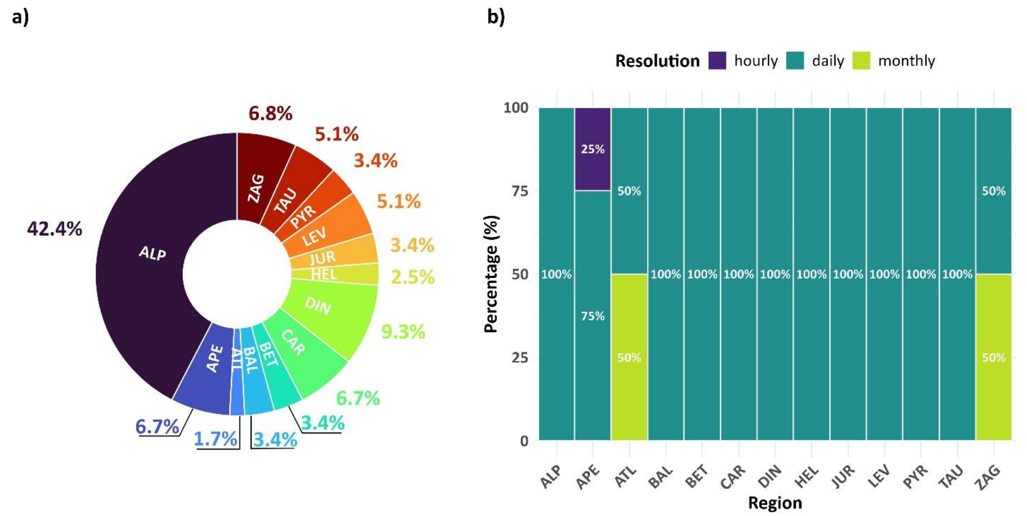

Figure 4: (a) The donut chart shows the regional distribution of karst springs according to number of karst springs, and (b) the stacked bars show the temporal resolution of the discharge time series in each region. (ALP: Alps, APE = Apennines, ATL = Atlas, BAL = Balkans, BET = Betics, CAR = Carpathians, DIN = Dinarides, HEL = Hellenides, JUR = Jura Mountains, LEV= Levant, PYR = Pyrenees, TAU = Taurus, and ZAG = Zagros Mountains)

3. Technical Validation

The technical validation of the dataset is grounded in the geological and hydrogeological coherence of the Euro-Mediterranean mountain belts, where karst development is primarily controlled by shared tectonic evolution, carbonate lithology distribution, and regional hydro-climatic gradients. Rather than treating individual springs as isolated observations, this study evaluates them within the context of the major orogenic systems that structure groundwater circulation across the Euro-Mediterranean, including the Atlas, Betics, Pyrenees, Alps, Carpathians, Apennines, Dinarides, Hellenides, Balkans, Taurus, Levant, and Zagros Mountains. These interconnected segments of the Alpine–Himalayan orogenic belt provide a natural framework for assessing data consistency, representativeness, and comparability, as they host analogous karst aquifer architectures formed under broadly similar geodynamic conditions but expressed across distinct climatic settings. The following subsections briefly outline the regional characteristics of these mountain systems to demonstrate how the compiled springs collectively capture the structural and environmental diversity necessary for robust large-scale analyses.

3.1 Regional Overview of the Mountains Systems

The karst systems of the Euro-Mediterranean mountain belts developed within carbonate platforms assembled during the closure of the Tethys Ocean and subsequent Alpine–Himalayan orogenesis, resulting in structurally comparable aquifers characterized by strong compartmentalization, steep hydraulic gradients, and high-relief recharge areas (Dewey et al., 1989; Stampfli & Borel, 2002; Stevanović, 2015). This shared orogenic framework provides a consistent structural basis for comparing spring discharge dynamics, while pronounced contrasts in latitude (from 30N to 50N), longitude (from 5W to 51E), elevation (from 19 to 2000 m asl), vegetation cover (from bare rock to dense forests), and precipitation regime introduce systematic variability in recharge seasonality, snow contribution, and evapotranspiration losses (Goldscheider et al., 2020; Bakalowicz, 2005; Giese et al., 2025). Consequently, the selected mountain systems collectively span a wide

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range of hydroclimatic conditions within a broadly similar tectonic setting, allowing the discharge dataset to capture both common structural controls and region-specific climatic signals; the following subsections briefly outline the regional characteristics that motivate the inclusion of each mountain belt in the dataset.

3.2 The Western Mediterranean Arc: Atlas, Betics, and Pyrenees

The Western Mediterranean mountain systems, including the Pyrenees, Betic Cordillera, and Atlas Mountains, host extensive karst aquifers developed within Mesozoic carbonate formations (Fig. 5) that act as major regional groundwater reservoirs under strong elevation- and climate-driven recharge gradients (Beauchamp et al., 1999; Akdim et al., 2012). Across these mountain belts, groundwater recharge is controlled by a combination of precipitation amount, snow accumulation, and melt seasonality, resulting in pronounced spatial and temporal variability in karst spring discharge. In the Pyrenees, high-elevation karst systems are primarily sustained by snow-dominated recharge, with seasonal storage and discharge strongly modulated by melt dynamics. This, in turn, conditions the development of the karst cave conduit system (González-Ramón et al., 2020). Groundwater flow is organized by thrust systems and folded carbonate structures, which compartmentalize aquifers and channel regional flow toward large karst springs (Muñoz, 1992; Vergés et al., 2002; Jódar et al., 2020). The Betic Cordillera exhibits highly heterogeneous hydroclimatic conditions, where episodic rainfall and mixed rain–snow recharge dominate. Structural compartmentalization related to the Alboran domain exerts first-order control on recharge–discharge connectivity and spring response variability (Platt & Vissers, 1989; Andreo et al., 2008). The Atlas Mountains represent a transitional Mediterranean to semi-arid hydroclimatic setting, where karst aquifers within Jurassic carbonate massifs provide long-term groundwater storage sustained by orographic precipitation and snowmelt at higher elevations (Frizon de Lamotte et al., 2009; 2011). These aquifers support perennial spring discharge despite limited annual rainfall and constitute a critical water resource during drought periods.

Across all three mountain systems, ongoing warming trends are altering snow persistence, melt timing, and recharge seasonality, increasing the sensitivity of karst spring discharge to interannual climate variability and prolonged droughts (Born et al., 2008; Beniston et al., 2018). The karst aquifers of the Atlas, Betics, and Pyrenees are therefore widely recognized as Mediterranean hydroclimatic hotspots and have been extensively studied from multiple hydrogeological perspectives (e.g., Mangin, 1975; Bouchaou et al., 2002; Sirieix et al., 2014; Akdim, 2015; Binet et al., 2020; Herms et al., 2019; 2021; Jódar et al., 2025). The major mountainous karst springs which are influenced by snowmelt recharge are given in Fig. 5 and Table 4. To better reveal the hydrodynamic behaviour of these systems, one candidate karst springs' discharge hydrograph from each region is shared in Fig. 6.

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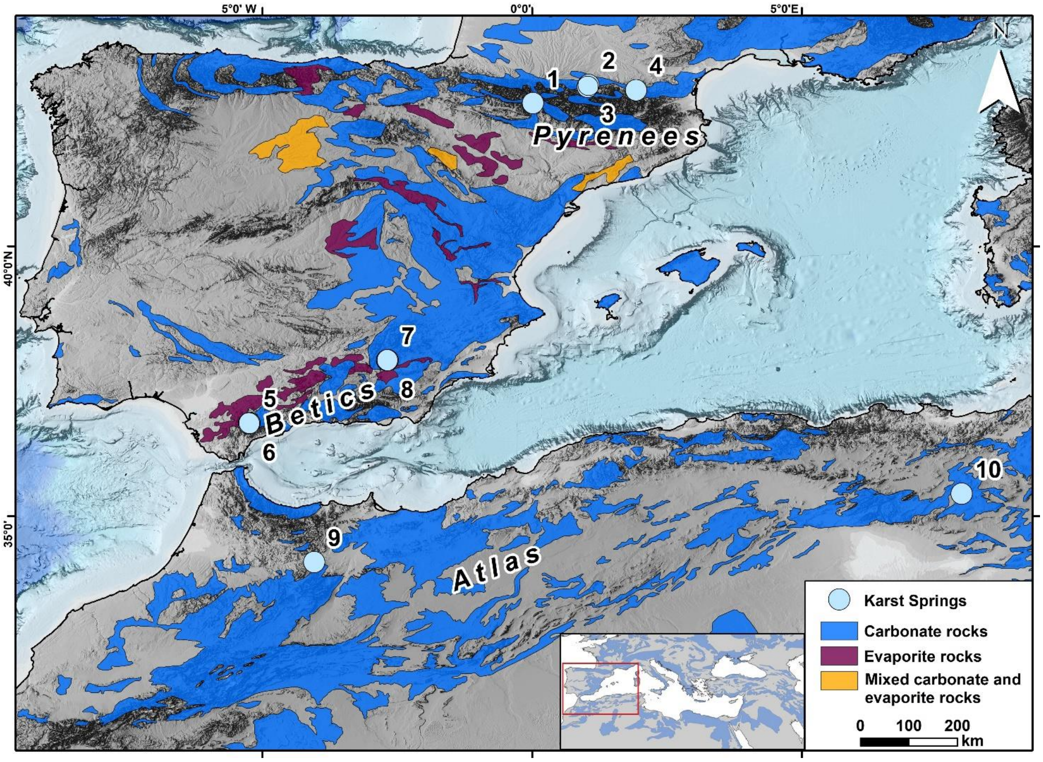


Figure 5: Distribution of major mountainous karst springs on the Mediterranean carbonate map within the large carbonate massifs of the Atlas, Betics, and Pyrenees mountains. Karst rocks are derived from the WoKAM dataset (Chen et al., 2017). Numbers shown on the springs refer to: 1 – Garcés Spring, 2 – Aliou, 3 – Baget–Las Hountas, 4 – Source de Fontestorbes, 5 – Cueva del Gato, 6 – Benaojan, 7 – Natividad, 8 – Fuente Alta, 9 – Ras El Ma (Taza), and 10 – Ain Youkous.

Table 4. The major karst springs in the Atlas, Betics, and the Pyrenees mountains

Region	**Country**	**Spring Name**	**Lat.**	**Lon.**	**Elev. (m asl)**	**Data period**	**Data resolution**
Atlas	Algeria	Ain Youkous	35.417	7.964	975	1973-1977	Daily
Atlas (Middle Atlas)	Morocco	Ras El Ma (Taza)	34.15	-4.04	960	1989-2020	Monthly
Betics	Spain	Cueva del Gato	36.727	-5.238	435	2009-2014	Daily
Betics	Spain	Benaojan	36.718	-5.251	520	2007-2017	Daily
Betics	Spain	Fuente Alta	37.888	-2.691	1140	2019-2022	Daily
Betics	Spain	Natividad	37.892	-2.676	1090	2019-2022	Daily
Pyrenees	France	Aliou	42.990	1.048	100	2009-2024	Daily
Pyrenees	France	Source de Fontestorbes	42.893	1.927	450	2019-2024	Daily
Pyrenees	France	Baget - Las Hountas	42.955	1.029	500	2020-2024	Daily
Pyrenees	Spain	Garcés	42.652	0.015	2000	2018-2025	Daily

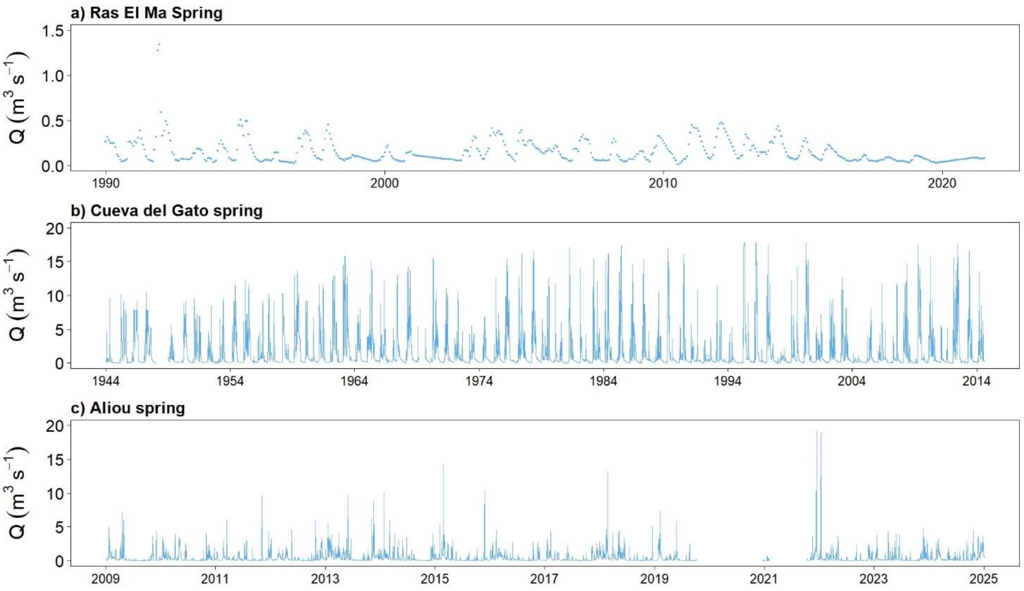


Figure 6. Discharge hydrographs from the Western Mediterranean karst mountains. (a) Ras El Ma spring from Moroccan Middle Atlas, (b) Cueva del Gato spring from Betics, and (c) Aliou spring from the French Pyrenees.

3.3 The North-Central European Arc: Jura, Alps and Carpathians

The Alpine–Carpathian mountain system hosts some of the most climatically sensitive karst aquifers in Europe, developed within thick Mesozoic carbonate successions whose hydraulic connectivity is strongly structured by Alpine–Tethyan tectonics (Dewey et al., 1989; Schmid et al., 2004). Karst aquifer geometry and conduit organization are fundamentally tectonogenetic, controlled by thrust systems, fold hinges, and fault zones inherited from multi-stage convergence and nappe stacking, while also commonly influenced by the direction of the groundwater hydraulic slope, by bedding planes as inherited sedimentary structures that are subsequently modified by tectonic deformation (Goldscheider et al., 2020). Across the Alps and the Jura Mountains, particularly within the Northern Calcareous Alps and Helvetic domain, karst aquifers exhibit dual hydraulic behaviour combining rapid conduit flow with slower fracture- and matrix-controlled storage. High-altitude massifs such as the Hochschwab sustain large perennial springs that form critical drinking-water resources for downstream urban areas (Goldscheider, 2005; Plan et al., 2009). Recharge is dominated by seasonal snow accumulation and melt, producing a pronounced nival discharge signal and strong interannual variability linked to winter precipitation and temperature conditions (Isotta et al., 2014). Eastward, the Western Carpathians represent a direct continuation of the Eastern Alps and karst aquifers typically occur as Mesozoic limestone and dolomite plates overthrust onto low-permeability foreland units. In these systems, groundwater recharge is likewise snow-controlled, and climatically driven shifts in snowmelt timing and duration are expected to alter spring discharge regimes and downstream groundwater contributions to lowland basins such as the Pannonian Basin (Royden, 1993; Csontos & Vörös, 2004; Matenco & Radivojević, 2012).

Overall, Alpine–Carpathian karst aquifers (Fig. 7) function as major "water towers" of Europe, where snowmelt-driven recharge and high structural connectivity result in rapid hydrological responses to climate variability. These systems have therefore been extensively investigated by hydrogeologists for decades from both process-based and applied perspectives (e.g. Klimchouk et al., 1996; Petrič, 2004; Malík, 2007; Orășeanu & Iurkiewicz, 2010; Cholet et al., 2017, 2019; Malík et al., 2021; Le Mesnil et al., 2022; Çallı et al., 2023; Gabrovšek et al. 2023). The major mountainous karst springs of the Alpine–Carpathian system are listed in Table 5. The discharge hydrographs from each mountain region is plotted in Fig. 8 to better illustrate the system hydrodynamics.

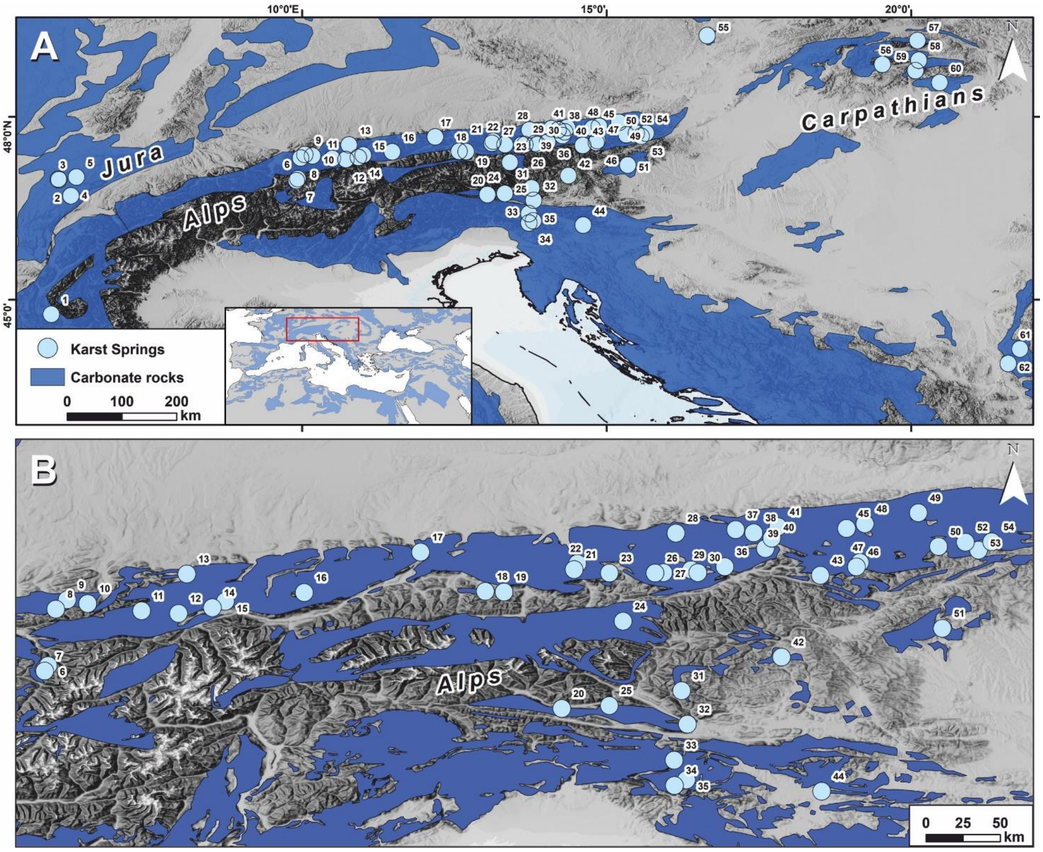


Figure 7. (A) Major karst springs associated with the Alpine–Carpathian karst aquifer systems in the North-Central European Arc, including the Jura Mountains, Alps, and Carpathians. Carbonate rocks are derived from the WoKAM dataset (Chen et al., 2017). (B) Closer view of the Alps shown in (A). Spring numbers correspond to: 1 – Gillardes, 2 – Lison, 3 – Verneau, 4 – Doubs, 5 – La Loue, 6 – Fidelisquelle, 7 – Obwaldquelle, 8 – Widumbachquelle, 9 – Goldbachquelle, 10 – Aubachquelle, 11 – Doserfall, 12 – Heiterwandquelle, 13 – Bergmannsquellen, 14 – Ursprungquelle (Lehnberg), 15 – Schwarzbach–Moosquelle, 16 – Schwarzlackenquelle, 17 – Blaue Quelle, 18 – Schreiende Brunnen, 19 – Pucherhäuslquelle, 20 – Lappenbachquelle, 21 – Schwarze Torrenquelle, 22 – Gollinger Wasserfall, 23 – Dachserfall, 24 – Marbachquelle, 25 – Fellbachquelle, 26 – Waldbachursprung, 27 – Hirschbrunn-Seeaustritt, 28 – Langwies/Miesbach, 29 – Ödensee-Kaltwassertrichter, 30 – Riedlbachquelle, 31 – Oswaldigquelle, 32 – Union Quelle, 33 – Soca, 34 – Tolminca, 35 – Savica, 36 – Sägtümpel, 37 – Brunnental, 38 – Teufelskirche, 39 – Prießling Ursprung, 40 – Rettenbachquelle, 41 – Steyrerquelle, 42 – Pöllauer Ursprung, 43 – Etzbachquelle, 44 – Kamniška Bistrica, 45 – Steinbachquelle, 46 – Wassermannsloch, 47 – Schwabeltalquelle, 48 – Reithbachquelle, 49 – Große Mühlquelle, 50 – Pfannbauernquelle, 51 – Hammerbachquelle, 52 – Totes Weib Quelle, 53 – Siebenquellen, 54 – Wasseralmquelle, 55 – Punkva, 56 – Dolná Lehota - Vrabec 2, 57 – Lysá Poľana - Tisovky, 58 – Liptovská Teplička - Macová, 59 – Muráň - Vyvieračka pod hradom, 60 – Slavec - Čierna vyvieračka, 61 – Vrelo Mlave, and 62 - Grza.

Table 5. The mountainous karst springs of the Alps-Carpathians regions (* 44 karst springs from Austria is given in supplementary material)

Region	Country	Spring Name	Lat.	Lon.	Elev. (m asl)	Data period	Data resolution
Alps	*Austria						
Alps	France	Gillardes	44.760	5.888	870	2015-2019	Daily
Alps	Slovenia	Kamniška Bistrica	46.224	14.617	385	1970-2023	Daily
Alps	Slovenia	Savica	46.293	13.797	838	1954-2024	Daily
Alps	Slovenia	Soca	46.412	13.724	990	1955-1982	Daily
Alps	Slovenia	Tolminka	46.259	13.725	680	1953-2024	Daily
Alps	Germany	Bergmannsquellen	47.539	10.772	1220	2018-2026	Daily
Jura Mts	France	Doubs	46.705	6.209	945	2009-2024	Daily
Jura Mts	France	La Loue	47.011	6.299	530	1993-2024	Daily
Jura Mts	France	Lison	46.967	6.011	420	1976-2024	Daily
Jura Mts	France	Verneau	46.978	6.002	375	1969-2024	Daily
Carpathians	Serbia	Grza	43.953	21.592	560	1988-1991	Daily
Carpathians	Serbia	Vrelo Mlave	44.192	21.784	320	1991-1999	Daily
Carpathians	Czechia	Punkva	49.333	16.650	300	1980-2023	Daily
Carpathians	Slovakia	Dolná Lehota - Vrabec 2	48.860	19.527	600	2016-2024	Daily
Carpathians	Slovakia	Liptovská Teplička - Macová	48.929	20.124	1100	2016-2024	Daily
Carpathians	Slovakia	Lysá Poľana - Tisovky	49.252	20.103	1000	2016-2024	Daily
Carpathians	Slovakia	Muráň - Vyvieračka pod hradom	48.757	20.070	430	2016-2024	Daily
Carpathians	Slovakia	Slavec - Čierna vyvieračka	48.562	20.465	250	2016-2024	Daily

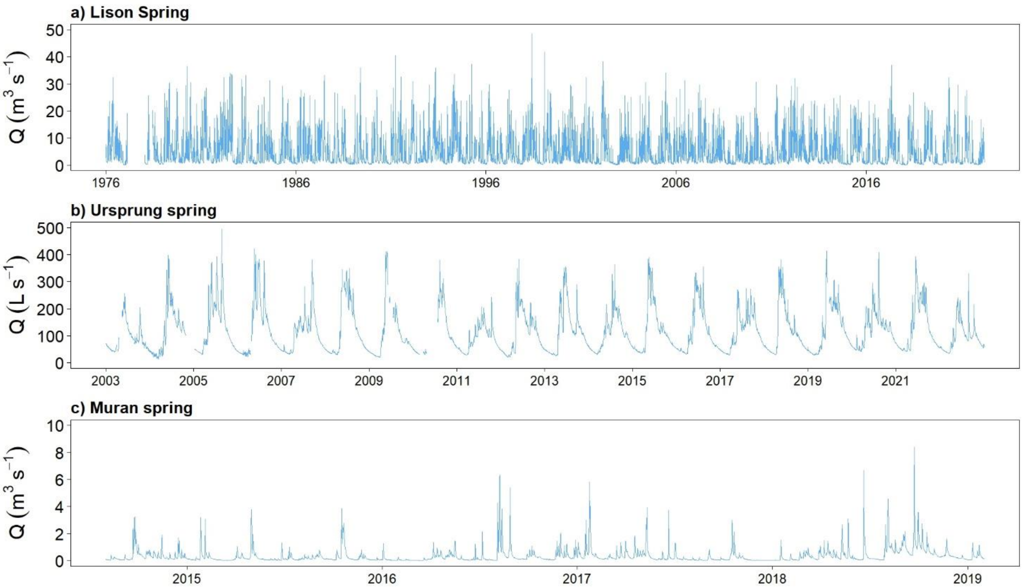


Figure 8: Discharge hydrographs from the Northern-Central Mediterranean karst mountains. (a) Lison spring from French Jura, (b) Ursprung (Lehnberg) spring from Austrian Alps, and (c) Muráň - Vyvieračka pod hradom from Slovakian Carpathians.

3.4 The Adriatic-Balkan System: Apennines, Dinarides, Hellenides and Balkans

The Adriatic–Balkan mountain system is included in the study because it hosts some of the most extensive and hydraulically responsive karst aquifers in Europe, spanning a broad latitudinal range and strong contrasts in elevation, vegetation cover, and Mediterranean climate regimes (Fig. 9).

The Apennine orogenesis developed through several tectonic phases producing a coupled system of eastward-migrating thrusting in the east and extensional faulting in the west (e.g., Carminati et al., 2010). This complex structural system, combined with pronounced hydroclimatic gradients, produced an intense karstification of limestone rocks which host aquifers feeding karst springs, most of which are located along the Apennine ridge (Xanke et al., 2024). In detail, karst aquifers of central Apennines, developed within thick Meso–Cenozoic carbonate Umbria–Marche Sequence and Lazio-Abruzzo carbonate platform. The mountain's elevations and the structural-geological complexity in a predominantly rainfall-driven recharge regime produce springs with pronounced seasonal variability and limited snow storage, making discharge sensitive to prolonged drought periods and reduced snow accumulation (Di Matteo et al., 2013; Lorenzi et al., 2023; Rusi & Di Giovanni, 2024; Di Matteo et al., 2026; Ortenzi et al., 2026). Moreover, the hydrogeological systems feeding the springs are located in high seismic areas which can produce abrupt discharge changes following earthquakes (e.g., Petitta et al., 2018; Di Matteo et al., 2020; Cambi et al., 2022).

The Dinarides represent the classical reference region for karst hydrogeology, characterized by high-relief carbonate plateaus, sparse soil and vegetation cover in the Adriatic zone, and intense winter precipitation. Northern parts (Snežnik, Velebit mountains), on the other hand, are densely forested which might have an influence on the groundwater recharge dynamics. These conditions, combined with structurally continuous carbonate units, promote rapid infiltration, limited hydraulic buffering, and the development of structurally-controlled (and frequently flooded) poljes (Mayaud et al., 2019; Ravbar et al., 2021), sinking rivers, and high-discharge springs such as Unica (Slovenia) and Ombla (Croatia) (Milanović, 1981; Bonacci, 2004; Mihevc et al., 2010). As a result, Dinaric karst springs exhibit strong interannual discharge variability and high sensitivity to prolonged droughts, with direct implications for regional drinking-water supply (Ćuk Đurović et al., 2022). The Hellenides form the southern continuation of the system into Albania and Greece, where higher elevations and mixed rainfall–snowmelt recharge coexist with strong tectonic compartmentalization. Karst aquifers hosted in carbonate platforms and marbles are highly responsive to both climatic forcing and seismic activity, frequently displaying abrupt discharge changes following earthquakes (Jolivet & Brun, 2010; Katsanou et al., 2015a, b; Katsanou, 2018; Eftimi & Malik, 2019; Eftimi, 2020). Across the Adriatic–Balkan region, karst groundwater constitutes a primary freshwater resource, and the springs compiled here (Table 6) provide critical records for assessing climate-driven variability in Mediterranean mountain karst systems. For further representation, discharge hydrographs are provided for one representative karst spring from each region in Fig. 10.

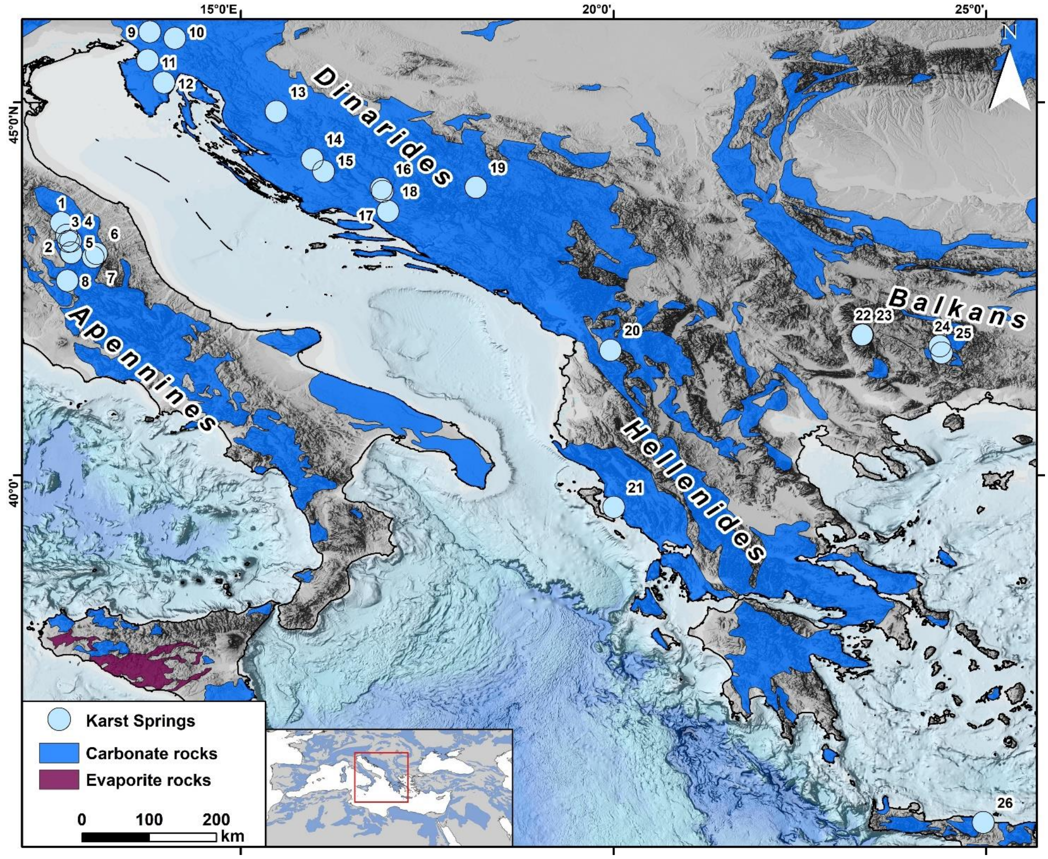


Figure 9: Distribution of the karst springs analyzed in this study across the Adriatic–Balkan mountain system, including the Apennines, Dinarides, Hellenides, and Balkan Mountains. Carbonate and evaporite rocks are derived from the WoKAM dataset (Chen et al., 2017). Numbers refer to the following karst springs: 1 – Scirca, 2 – Boschetto, 3 – San Giovenale, 4 – Bagnara, 5 – Rasiglia Alzabove, 6 – Ussita, 7 – Castelsantangelo, 8 – Lupa, 9 – Hubelj, 10 – Unica, 11 – Rižana, 12 – Grobnik Posert, 13 – Vrbica Ričice, 14 – Vrelo Zrmanja, 15 – Izvor Krka, 16 – Gorni Zabljak, 17 – Vrelo Sturbe, 18 – Plitvička Ljeskovac, 19 – Vrelo Bosne, 20 – Selita, 21 – Blue Eye (Syri-i Kalter), 22 – Yazo, 23 – Kyoshka, 24 – Vrisa Beden, 25 – Mugla, and 26 – Almyros.

Table 6. The mountainous karst springs of the Apennines, Dinarides, and Balkan regions

Region	Country	Spring Name	Lat.	Lon.	Elev. (m asl)	Data period	Data resolution
Apennines	Italy	Castelsantangelo	42.894	13.157	738	2006-2026	Daily
Apennines	Italy	Ussita	42.942	13.202	1350	2021-2026	Daily
Apennines	Italy	Scirca	43.354	12.730	590	2007-2024	Daily
Apennines	Italy	San Giovenale	43.103	12.826	475	1998-2024	Daily
Apennines	Italy	Rasiglia Alzabove	42.952	12.864	630	1998-2024	Daily
Apennines	Italy	Boschetto	43.186	12.802	540	2007-2024	Daily
Apennines	Italy	Bagnara	43.109	12.856	630	1998-2024	Daily
Apennines	Italy	Lupa	42.579	12.812	375	1997-2024	Daily
Dinarides	Bosnia and Herzegovina	Vrelo Bosne	43.827	18.271	497	2007-2019	Daily

Dinarides	Bosnia and Herzegovina	Vrelo Sturbe	43.774	17.023	738	2004-2019	Daily
Dinarides	Bosnia and Herzegovina	Gorni Zabljak	43.808	17.007	721	2007-2019	Daily
Dinarides	Croatia	Plitvička Ljeskovac	43.509	17.096	410	2001-2023	Daily
Dinarides	Croatia	Grobnik Posert	45.228	14.102	45	1999-2023	Daily
Dinarides	Croatia	Vrbica Ričice	44.839	15.603	687	1996-2023	Daily
Dinarides	Croatia	Izvor Krka	44.042	16.235	245	1947-2014	Daily
Dinarides	Croatia	Vrelo Zrmanja	44.203	16.083	325	1977-2014	Daily
Dinarides	Slovenia	Unica	45.820	14.246	453	1926-2024	Daily
Dinarides	Slovenia	Hubelj	45.905	13.913	220	1955-2024	Daily
Dinarides	Slovenia	Rižana	45.528	13.885	69	1947-2024	Daily
Hellenides	Greece	Almyros	35.339	25.049	19	1999-2001	Daily
Hellenides	Albania	Blue Eye (Syri-i Kalter)	39.552	20.113	152	1968-1973	Daily
Hellenides	Albania	Selita	41.651	20.069	881	1966-1986	Daily
Balkans	Bulgaria	Yazo	41.855	23.427	942	1963-2018	Daily
Balkans	Bulgaria	Kyoshka	41.854	23.436	912	1963-2018	Daily
Balkans	Bulgaria	Vrisa Beden	41.706	24.466	800	2000-2022	Daily
Balkans	Bulgaria	Mugla	41.616	24.493	1340	2000-2022	Daily

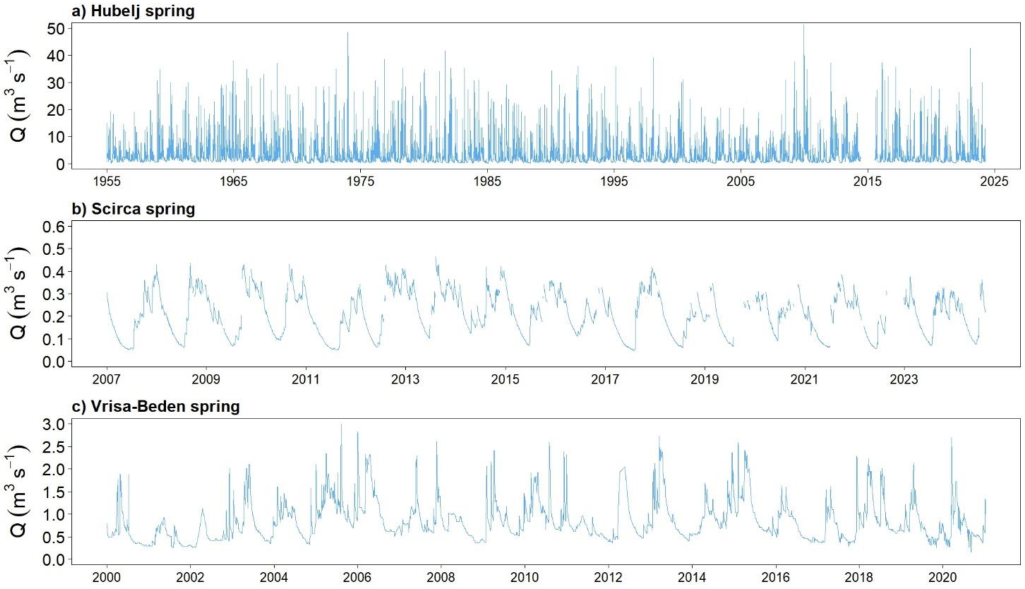


Figure 10: Hydrograph plots of the Adriatic Balkan system karst springs. (a) Hubelj spring from Slovenian Dinarides, (b) Scirca spring from Italian Apennines, and (c) Vrisa-Beden spring from Bulgarian Balkans.

3.5 The Eastern Mediterranean Belt: Taurus, Levant, and Zagros

The Eastern Mediterranean karst belt is included in the study because it spans some of the strongest gradients in elevation, vegetation, and climate across the Euro-Mediterranean domain, while sharing a common Alpine–Tethyan orogenic framework that hosts laterally extensive carbonate aquifers (Fig. 11) (Beydoun, 1977; Şengör & Yılmaz, 1981; Alavi, 2004; Asmael et al., 2015; Burg & Gev, 2019). This combination provides an ideal setting to examine how contrasting hydroclimatic forcing—rather than lithological differences—controls the spatial and temporal variability of karst spring discharge. In the Taurus Mountains of southern Türkiye, many high mountain elevations (>2,000 m) consisting of dissolution dolines (Öztürk et al., 2018), persistent seasonal snowpack produce recharge regimes dominated by snow accumulation and melt (Çallı et al., 2022; Çallı, 2026). Karst aquifers developed within folded and overthrust carbonate nappes exhibit steep hydraulic gradients and deep subsurface drainage, generating large springs (e.g. Dumanlı and Kapuzbaşı springs) whose discharge timing and magnitude are highly sensitive to changes in snow persistence, melt onset, and precipitation phase (Bayari et al., 2009; De Waele et al., 2011; Stevanović, 2015; Çelik & Çallı, 2021; Çelik et al., 2022; 2024). The high Levant karst systems, extending across Lebanon (Edgel, 1997; Doummar et al., 2018; Dubois et al., 2020), western Syria, and Northeast Israel (Mount Hermon) (Ben-Zur et al., 2025), represents a transitional hydroclimatic setting in which high-altitude snow-fed recharge sustains major perennial springs. Lower-elevation and coastal karst aquifers respond rapidly to rainfall variability and storage limitation and show increased sensitivity of the groundwater to climate change and increasing production (e.g., Rimmer & Salingar, 2006; Bakalowicz et al., 2008; Dafny et al., 2010). Further east, the Zagros Mountains extend the belt into a continental and semi-arid climate regime, where recharge is concentrated during the winter wet season and locally supplemented by high-elevation snow accumulation. Karst aquifers hosted in thick carbonate successions display strongly seasonal discharge and limited hydraulic buffering, making Zagros springs particularly sensitive to interannual precipitation variability and prolonged droughts (Karimi et al., 2005; Mohammadi et al., 2007; Raeisi & Stevanović, 2010; Kavousi & Raeisi, 2015; Geravand et al., 2022; Zeydalinejad et al., 2025; Mohammadi-Ahmadmahmoudi et al., 2025). Some major karst springs of the Eastern Mediterranean mountains are listed in Table 7. For a broader representation, one candidate karst spring discharge hydrographs from each region is shared in Fig. 12.

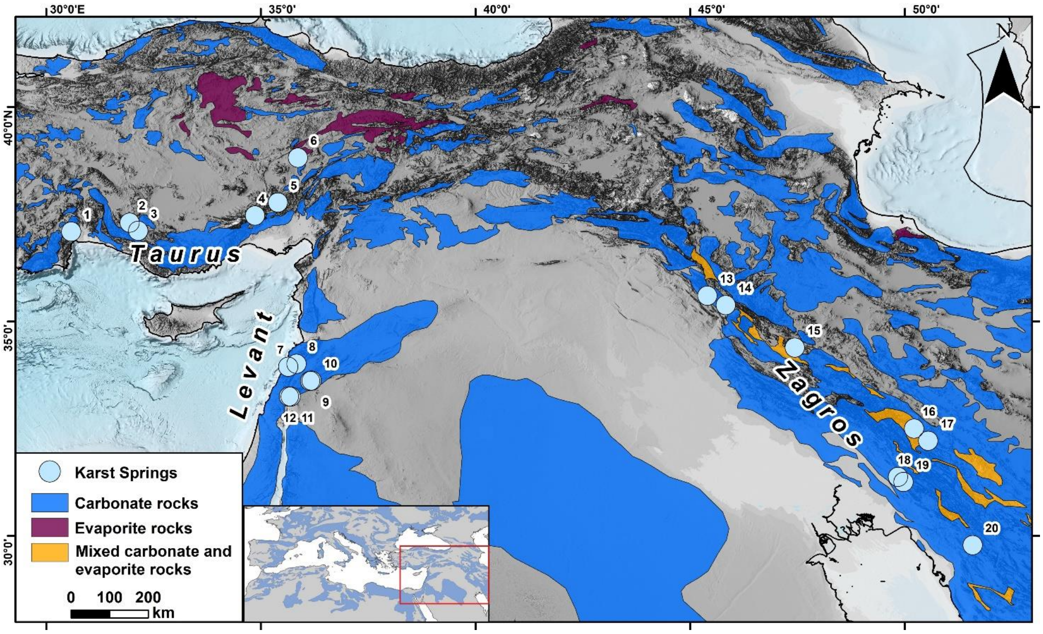
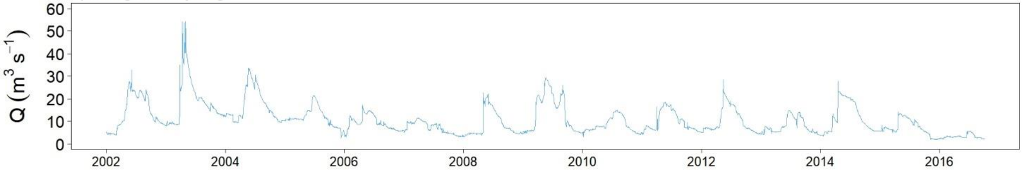


Figure 11: Distribution of mountainous karst springs in the Eastern Mediterranean across the Taurus, Levant, and Zagros mountain belts. Karst rocks are derived from the WoKAM dataset (Chen et al., 2017). Numbers refer to the following karst springs: 1 – Kırkgözler, 2 – Pınarbaşı, 3 – Aygırdibi, 4 – Şekerpınarı, 5 – Kapuzbaşı, 6 – Tacin, 7 – Qachqouch, 8 – Assal, 9 – Fageh, 10 – Figeh, 11 – Dan, 12 – Banias, 13 – Sarchinar, 14 – Sarchawi Saraw, 15 – Biston, 16 – Dimeh, 17 – Pirghar, 18 – Barme-Jamal, 19 – Poto, and 20 – Sasan.

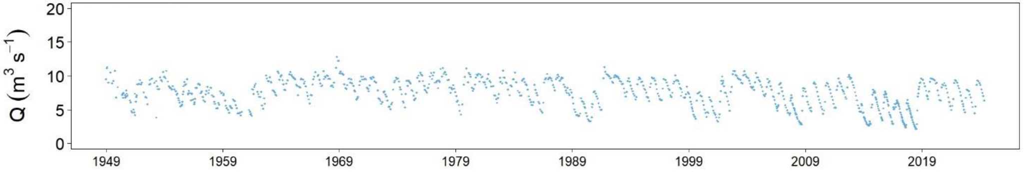
Table 7. The mountainous karst springs of the Eastern Mediterranean regions

Region	**Country**	**Spring Name**	**Lat.**	**Lon.**	**Elev. (m asl)**	**Data period**	**Data resolution**
Levant	Lebanon	Assal	34.010	35.828	1390	2014-2018	Daily
Levant	Lebanon	Qachqouch	33.944	35.638	56	2014-2018	Daily
Levant	Syria	Fageh	33.613	36.147	887	1987-2005	Daily
Levant	Syria	Figeh	33.618	36.181	853	1987-2005	Daily
Levant	Israel	Banias	33.248	35.695	390	1989-1999,1968-2026	Daily, monthly
Levant	Israel	Dan	33.249	35.653	195	1989-1999,1949-2026	Daily, monthly
Taurus	Türkiye	Pınarbaşı	37.302	31.942	1099	2014-2025	Daily
Taurus	Türkiye	Şekerpınarı	37.468	34.863	840	2011-2024	Daily
Taurus	Türkiye	Kapuzbaşı	37.771	35.396	660	2011-2017	Daily
Taurus	Türkiye	Tacin	38.815	35.864	1465	2003-2019	Daily
Taurus	Türkiye	Kırkgözler	37.094	30.581	300	2003-2017	Daily
Taurus	Türkiye	Aygırdibi	37.113	32.141	1100	2003-2019	Daily
Zagros	Iran	Barme-Jamal	31.375	49.840	490	2003-2011	Daily
Zagros	Iran	Poto	31.256	49.968	675	2010-2017	Daily
Zagros	Iran	Biston	34.390	47.437	1290	1970-2009	Monthly
Zagros	Iran	Dimeh	32.501	50.215	2220	1998-2013	Monthly
Zagros	Iran	Pirghar	32.217	50.544	2016	1998-2014	Monthly
Zagros	Iran	Sasan	29.783	51.583	820	1985-2012	Monthly
Zagros	Iraq	Sarchinar	35.600	45.400	1625	2002-2003	Daily
Zagros	Iraq	Sarchawi Saraw	35.380	45.830	515	2004-2006	Daily

a) Kırkgozler spring



b) Dan spring



c) Biston spring

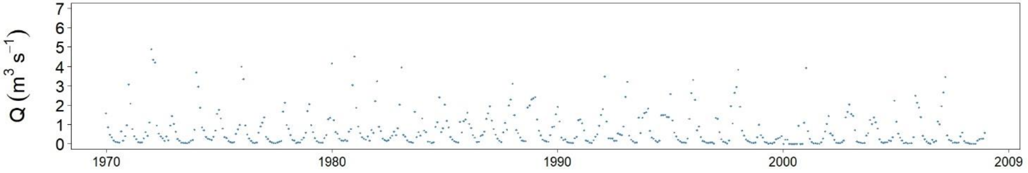


Figure 12: Discharge hydrograph of the Eastern Mediterranean karst springs. (a) Kırkgözler from Taurus, (b) Dan spring from Mount Hermon (Levant), and (c) Biston spring from Iranian Zagros.

4. Data Availability

The complete dataset is available publicly at Zenodo platform: https://doi.org/10.5281/zenodo.19448791). Çallı et al. (2026).

5. Conclusions and Future Outlook

This study establishes a comprehensive synthesis of karst spring discharge datasets across the Euro-Mediterranean region, providing a critical empirical foundation for regional hydrological modelling. Such efforts are paramount for enhancing our predictive capabilities regarding the behaviour of these systems within a recognized climate hotspot. While the KaMERaMAN database offers significant insights into the dynamics of these complex aquifers, it is important to acknowledge that geographic representation remains non-uniform. These spatial disparities primarily reflect the inherent challenges of monitoring karst systems in remote or topographically complex terrains. Mountainous environments, though vital for regional water security, present formidable logistical barriers to the installation and maintenance of high-resolution monitoring infrastructure. Beyond physical constraints, data acquisition is often limited by varying levels of institutional engagement and systemic monitoring gaps. For instance, despite extensive outreach to researchers across the Atlas region—an area characterized by significant mountainous karst springs such as Ain Asserdoune and Ain Aflafal—the scarcity of long-term, high-resolution discharge records resulted in the inclusion of only two stations from this region.

6. Author Contributions

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Visualization: Süleyman Selim Çallı, Ergin Gökkaya

Supervision: Andreas Hartmann

7. Competing Interests

The authors declare that they have no financially competing interests.

8. Acknowledgment

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their support. We extend our sincere gratitude to the contributors who facilitated data access, as collaborative transparency is indispensable for addressing climate-driven uncertainties in karst environments. We invite the broader hydrogeological community to engage in this ongoing dialogue, ensuring that future iterations of this dataset achieve a more balanced and robust representation of these critical water resources.

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