Acta Geologica Polonica, Vol. 76 (2026), No. 4, e96
DOI: 10.24425/agp.2026.158210

Characterizing local mountain groundwater systems through spring discharge variability: a case study from the Sudetes

TOMASZ OLICHWER

Institute of Geological Sciences, University of Wroclaw, pl. M. Borna 9, 50-204 Wroclaw, Poland,
e-mail: tomasz.olichwer@uwr.edu.pl

ABSTRACT

Olichwer, T. 2026. Characterizing local mountain groundwater systems through spring discharge variability: a case study from the Sudetes. *Acta Geologica Polonica*, **76** (4), e96.

This study evaluates whether long-term spring-discharge records can be used to distinguish modes of functioning of local mountain aquifer systems in the Sudetes (SW Poland). Four springs representing three hydrogeological settings were analysed: porous-fractured Cretaceous sedimentary rocks, weathering mantles and fractured crystalline rocks, and weathering mantles developed on volcanogenic rocks. The methodology combined statistical measures of discharge variability, flow duration curves, the Pardé coefficient, autocorrelation and cross-correlation analyses, master recession curves and baseflow index interpretation. The Szczytna spring, draining a sedimentary aquifer system, represents the most stable flow regime, with the highest retention capacity and the greatest resistance to short-term variability in recharge. The Kowary and Różanka springs display intermediate characteristics, typical of shallow groundwater circulation systems developed within weathering mantles and fractures in crystalline rocks. The Kowalowa spring is characterized by the most dynamic response to recharge, high discharge variability, and the fastest depletion of groundwater resources. The obtained results should be regarded as indicative, as the analysis is based on weekly data and does not include independently delineated spring recharge areas. Nevertheless, the study demonstrates that long-term spring discharge records can support a process-based interpretation of retention and drainage in poorly investigated mountainous aquifer systems.

Key words: Sudetes; Mountain aquifers: Flow duration curve; Aquifer memory; Recession analysis; Baseflow index; Hydrogeological drought.

INTRODUCTION

Springs represent a direct expression of groundwater circulation within the rock environment (Meinzer 1923). One way to assess the hydrodynamic behaviour of aquifer systems is to analyse the discharge variability of springs draining these systems (Bonacci 1993; Amit *et al*. 2002). This is particularly important in mountainous areas, where groundwater resources depend strongly on storage within weathered, fractured and porous zones, while also being sensitive to seasonal variations in recharge, snowmelt and periods of hydrogeological drought. Where piezometric, hydrochemical or modelling data are limited, spring-discharge analysis can provide practical information on storage capacity, drainage rates and system resilience to periods of recharge deficit (Negi and Joshi 1996; Hayashi 2020). The methodology of spring research is based, among other things, on the assumption that the more water-rich the aquifers are, the more slowly their resources are depleted, which is reflected in more stable and sustained spring discharge (Maillet 1905; Krešić 2010). To assess spring-discharge variability, various coefficients are used, including the SCVP (spring coefficient of variation parameter) (Springer *et al*. 2004) and the Pardé coefficient (Weingartner *et al*. 2013). Flow duration curves (FDCs) are also used, as they

© 2026 Tomasz Olichwer. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/), which permits use, distribution, and reproduction in any medium, provided that the article is properly cited.

present spring-discharge variability in a different way and, based on their shape, can provide insight into the nature of rock voids controlling groundwater circulation in the rock mass (Vogel and Fennessey 1995). Time-series analysis is also fundamental to spring-discharge studies; one example is spring-discharge autocorrelation (ACF), which reflects the aquifer memory effect (Mayaud *et al*. 2014). Cross-correlation analysis (CCF), which examines the relationship between precipitation and spring discharge, is also commonly used (Mangin 1984). Master recession curve (MRC) analysis is another standard component of spring research, allowing recession components to be separated and, ultimately, the storage capacity and hydrogeological parameters of the groundwater reservoir to be determined (Toebes *et al*. 1969; Nathan and McMahon 1990; Tallaksen 1995; Posavec *et al.* 2010).

Spring research has been conducted in the Sudetes for many years (Kowalski 1983; Kryza and Kryza 1983; Kryza and Tarka 1992; Buczyński *et al.* 2011), focusing primarily on the quantitative assessment of groundwater resources in local reservoirs. In such assessments, recession-curve analysis of spring discharge is particularly useful. Research on karst springs in the Sudetes by Bocheńska *et al.* (2002) showed recession coefficient values of the order of 10^{-3}, corresponding to a local groundwater-reservoir storage capacity of approximately 450,000 m³. The calculated residence time of karst waters in the aquifer system was 115 days. Other studies indicate that springs draining erlan rocks are characterized by lower recession coefficients and, therefore, by higher storage capacity of the reservoirs feeding these outflows than springs emerging from fractured gneisses and their overlying weathering mantles (Kryza and Tarka 1992). The low storage capacity of shallow gneiss groundwater reservoirs in the Sudetes is confirmed by the work of Marszałek (1996). The calculated recession coefficients ranged from 0.0129 to 0.0159, indicating rapid depletion of groundwater resources. Relatively high storage-capacity values for shallow groundwater reservoirs within crystalline rocks (excluding crystalline limestones), reaching up to 22,000 m³, are observed in deeper zones of fractured granite and quartz rocks, as well as in highly permeable granite debris and rubble (Marszałek 1996). Other studies show that local groundwater reservoirs developed in fractured Cretaceous sedimentary rocks may be as water-rich as karst reservoirs. These reservoirs are characterized by recession coefficients of the order of 10^{-3}, significant storage capacity (over 250,000 m³) and greater spring-discharge stability than reservoirs developed in weathered and fractured crystalline rocks (Olichwer 2023).

In this study, analyses of discharge variability in four selected springs from the Sudetes (SW Poland) were used to characterize three types of local groundwater systems occurring in mountainous areas. The first type is associated with a rock mass composed of porous and fractured Cretaceous sandstones, mudstones, and marls. The second type is related to weathering mantles and highly fractured crystalline rocks. The third type is associated with weathering mantles and fractured volcanic rocks.

The main research question addressed in this study is whether classical methods used to analyse spring discharge variability can reliably distinguish between types of local mountain aquifer systems in terms of groundwater storage, drainage rates, and resilience to low-flow periods. It was hypothesised that springs draining reservoirs with greater storage capacity and deeper groundwater circulation should exhibit lower discharge variability, a longer statistical memory effect in the hydrograph, lower recession coefficients, and a higher contribution of baseflow than springs fed by shallow and permeable weathered-fractured zones. Therefore, the aim of the study is not only to describe individual parameters, but primarily to provide their integrated, process-based interpretation as indicators of the functioning of local groundwater systems. Owing to the limited number of springs analysed, the results are treated as a comparison of local conceptual models of aquifer system functioning in the Sudetes, rather than as a universal classification of all mountain groundwater systems. An additional objective is to highlight the potential and limitations of the applied set of techniques, taking into account that each of the analysed lithological groups is represented by a small number of sites, and that the results may be modified by local factors such as recharge area size, elevation, snow cover, or the local fracture network.

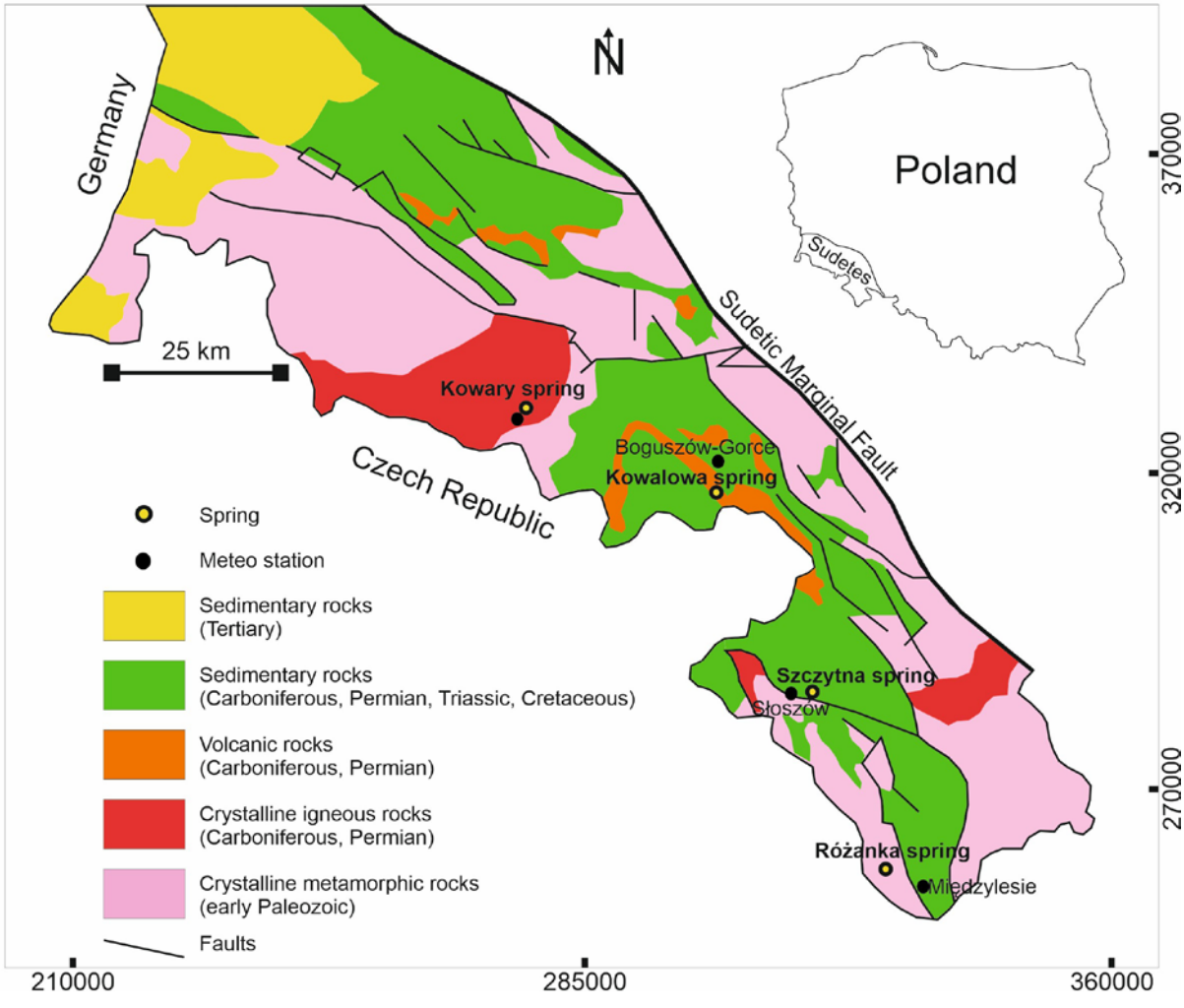
The novelty of this study lies not in the application of any single analytical method, but in assessing whether several independent characteristics based on spring discharge can provide a coherent, process-based assessment of how diverse aquifer systems function in the Sudetes. Previous studies of Sudetic springs (Buczyński 2018; Bartnik and Moniewski 2019; Olichwer 2023) focused primarily on discharge variability and parameters derived from recession analysis, whereas the present study integrates the results of FDC, ACF and CCF analyses, MRC segmentation, and hydrograph filtering.

STUDY AREA

The four springs selected for the study are located in the Sudetes, a typical fault-block mountain range with a NW-SE orientation (Text-fig. 1). The present-day morphology of the study area results from young block deformations during the Neogene, together with long-term weathering, erosion and denudation processes that exposed rocks at the surface. The Sudetes have a mosaic geological structure, with igneous, metamorphic and sedimentary rocks exposed at the surface, ranging in age from the Proterozoic through the Palaeozoic and Mesozoic to the Cenozoic (Mazur *et al*. 2007).

The described springs are drainage bases for groundwater circulating in different hydrogeological settings within the study area. At Szczytna spring (Text-fig. 1), groundwater circulating in Cretaceous sedimentary rocks, represented by sandstones, mudstones and marls, discharges at the surface. This outflow includes water originating from both shallow and deeper groundwater circulation systems. Under these hydrogeological conditions, two aquifers (upper and lower) are distinguished within the fractured and porous rocks, separated by a complex of poorly permeable sediments. In tectonically disturbed areas, these aquifers remain in hydraulic contact. The depth to the aquifer ranges from a few metres to 300 m. The thickness of the aquifer formations is variable and averages 60–80 m for the upper aquifer and 30–50 m for the lower aquifer (Kowalski 1983).

The outflows in Różanka and Kowary are associated with weathering mantles overlying highly fractured crystalline rocks (Text-fig. 1). The outflow in Kowalowa is also associated with weathering mantles, but developed on fractured sedimentary rocks of volcanic origin. In these hydrogeological settings, two groundwater zones are distinguished. The upper



Text-fig. 1. Location of the investigated springs in the Sudetes, modified after Dadlez *et al.* (2000).

Spring	Coordinate system 1992		Elevation m (a.s.l.)	Rock type	Age of rocks
	x	y			
Szczytna	317969.69	286931.85	468.7	sandstone, mudstone	Upper Cretaceous
Kowary	278555.08	331415.72	512.5	granite	Upper Carbon
Kowalowa	302260.33	317512.87	567.5	tuffs, tuffites	Lower/Middle Permian
Różanka	330342.89	258403.39	522	mica schist	Proterozoic/Paleozoic

Table 1. Descriptions of springs.

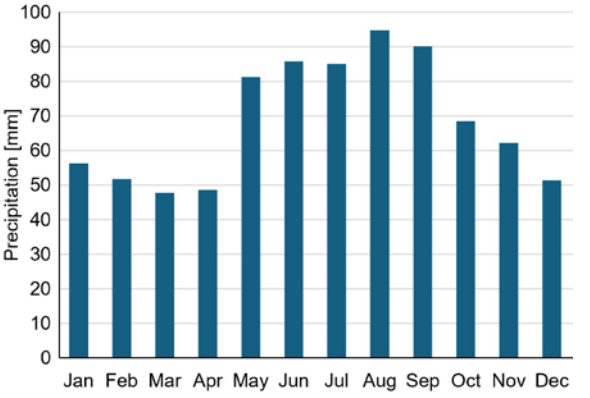
zone occurs in the near-surface and weathered part of the rocks, with an unconfined or slightly confined groundwater table, being in hydraulic connection with the underlying highly fractured rock mass. This zone extends to a depth of about 40 m. The second zone, called the lower zone, is associated with deeper water circulation in the fissure and fracture system in areas of tectonic rock loosening (depth up to 150 m). The thickness of the water-bearing formations is varied and reaches up to 40 m (Staśko *et al*. 2010). The Różanka, Kowary, and Kowalowa springs drain the upper aquifer zone, where the local groundwater circulation system is manifested.

Szczytna spring, located at an elevation of 468.7 m a.s.l., is an ascending, fissure-stratified spring (Table 1). Water discharges from the contact zone between Upper Cretaceous sandstones and mudstones (upper aquifer). The spring is located on a gentle valley slope. The spring in Różanka has a descension character, of a slope type, and is located at an elevation of 522 m a.s.l. Hydrogeologically, it is associated with fractured and weathered Early Palaeozoic metamorphic rocks (mica schists and gneisses). Kowalowa spring, located at an elevation of 567.5 m a.s.l., is a descending spring. Hydrogeologically, it is associated with weathered Permian volcanites represented by tuffs and tuffites. The spring drains the near-surface water-bearing zone within sedimentary rocks, reaching a depth of about 15 m (Wojtkowiak 2002). Kowary spring, located at an elevation of 512.5 m a.s.l., is a descending debris-slope spring. It drains weathering mantles to a depth of 15 m and the fissure-fracture system to a depth of 40 m, both developed in granite rocks (Grzegorczyk 2002).

The climate of the study area is a temperate, humid mountain climate. The average annual air temperature in the elevation range where the described springs occur is 6–7°C (Tomczyk and Bednorz, 2022). Based on data from 4 stations located near the springs (Text-fig. 1), the average annual total precipitation in the multi-year period 2014–2025 ranged from 733 to 853 mm (Table 2). The lowest annual precipitation totals were recorded in 2015, while the highest in 2024 (Table 2). The season with the highest precipitation is summer (June–September). The lowest monthly precipitation totals are recorded in winter (December–March) (Text-fig. 2).

In south-western Poland, 2015 was classified as an extremely dry year, with the precipitation deficit leading to a substantial decline in spring discharge. In Sudetic catchments underlain by sandstones, marls or Quaternary deposits, reductions of around 14–22% were observed. In contrast, springs draining rocks such as granites, gneisses, schists and tuffs, recharged mainly through fracture systems and weathered zones, exhibited much greater decreases in discharge, ranging from 50 to 72% (Staśko and Buczyński 2018).

Within the 400–600 m a.s.l. elevation belt in the Sudetes, snow cover persists for approximately



Text-fig. 2. Mean monthly precipitation.

	Słoszów	Kowary	Boguszów-Gorce	Międzylesie	Average
2014	682	894	834	796	801
2015	633	544	476	659	578
2016	744	894	710	722	767
2017	875	854	785	892	851
2018	673	579	548	613	603
2019	791	697	670	850	752
2020	869	952	904	1036	940
2021	858	971	832	837	874
2022	921	770	656	854	800
2023	1041	917	788	1065	952
2024	895	957	839	1185	969
2025	536	833	747	729	711
Mean	793	822	733	853	800

Table 2. Annual precipitation [mm].

70–100 days. According to Urban *et al*. (2023), in this part of the altitudinal profile, the actual duration of snow-cover persistence accounts for only about 45–50% of the potential period, which indicates frequent breaks in continuous snow cover. This pattern is supported by meteorological data from 2014–2025 for the study area, where the cumulative annual duration of snow cover ranged from 17 days in 2014 to 65 days in 2021.

DATA AND METHODS

This study is based on weekly discharge data from four springs belonging to the groundwater monitoring network operated by the Polish Geological Survey. The dataset covers the period from 6 January 2014 to 29 December 2025. Discharge measurements are performed manually at weekly intervals, every Monday at 06:00 UTC. Following data-quality verification, the measurements are submitted to the database once a month. Rectangular weirs are used for the measurements: the head of water over the weir is recorded, and discharge is subsequently calculated using the calibration equation established for each individual weir. The analyses were based exclusively on discharge values provided at a consistent weekly time step. This limitation is particularly relevant for low-discharge springs, such as Kowary and Różanka, where even minor absolute measurement errors may significantly affect variability indices. It is also important for the highly dynamic Kowalowa spring, where weekly measurements may not capture short-duration discharge peaks or the initial phases of recession.

Data on monthly precipitation totals at 4 meteorological stations (Słoszów, Kowary, Boguszów-Gorce, Międzylesie) located near individual springs (Text-fig. 1) were also used. Precipitation data were obtained from the publicly available database maintained by the Institute of Meteorology and Water Management (https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/).

The applied methodology comprises several integrated components that allow the dynamics and temporal variability of spring discharge to be assessed, as well as the properties of the aquifers drained by the springs to be determined.

In the first stage, statistical analysis was performed to assess the discharge variability of the analysed springs. In addition to the standard parameters presented in Table 3, the analysis included the spring coefficient of variation parameter (SCVP), defined as the ratio of the standard deviation of discharge to mean spring discharge (Springer *et al.* 2004). To assess discharge variability and gain insight into the frequency and duration of low-flow conditions in the springs, flow duration curves (FDCs) were also used. An FDC shows the percentage of time during which spring discharge equals or exceeds a given value. Furthermore, the Pardé coefficient P [–] was applied to characterize the mean seasonal variability of spring discharge (Weingartner *et al*. 2013). In the present study, P was calculated as the ratio between the mean discharge for a given month, averaged across all observation years, and the mean discharge for the entire period 2014–2025. Although the Pardé coefficient was originally used in river-flow analysis, it has also been applied in studies of spring discharge (Seelig *et al*. 2024).

In the next stage, autocorrelation analysis (ACF – autocorrelation function) was performed to estimate the aquifer memory effect (Mayaud *et al.* 2014; Fatoni *et al.* 2024), calculated on the basis of the time required for the autocorrelogram to reach a value of $r(k) = 0.2$ (Mangin 1984). In this study, the term 'memory effect' denotes a statistical property of the discharge time series, i.e. the extent to which current discharge values are dependent on previous values. It is not directly equivalent to the actual residence time of water within the reservoir; however, it may indirectly reflect the capacity of the system to store water and release it gradually. In the ACF analysis, weekly spring-discharge values were used, with time lags ranging from 0 to 19 weeks. Cross-correlation function (CCF) analysis was also carried out between mean monthly spring discharge and monthly precipitation totals, considering lag times of 0–12 months. The results were interpreted as a preliminary indication of the spring response to recharge, rather than as a full analysis of infiltration processes, snow storage or evapotranspiration. ACF and CCF analyses were performed using Excel.

The next methodological part included the analysis of spring-discharge recession curves over time, by generating MRCs and FDCs. For this purpose, the MRCTools v3.1 tool (Excel spreadsheet) was used, based on algorithms presented in the works of Posavec *et al.* (2006, 2010, 2017). This tool was used not only to generate recession curves and determine recession coefficients α, but also to divide these curves optimally into separate segments representing different recession phases (early, intermediate and late). Recession periods were automatically identified by the software from the continuous spring-discharge time series as sections representing individual recession events. Each section was treated as a separate recession segment. The segments were then sorted according to their initial discharge, from the

highest to the lowest value. Once the segments had been identified and sorted, the first segment was fitted with five regression models: linear, logarithmic, second-degree polynomial, power and exponential. The best-fitting model was selected on the basis of the coefficient of determination, R^2. The second recession segment was then shifted along the time axis so that its initial point coincided with the regression curve of the first segment. After the two segments had been combined, the regression was recalculated; the third segment was then fitted in the same way, and the procedure was repeated until all segments had been processed and merged into a single MRC (Posavec *et al*. 2006). The software generated 43 recession events for Szczytna, 28 for Różanka, 47 for Kowalowa and 38 for Kowary.

When the MRC was segmented into three components, the master recession curve was again first constructed from the individual recession segments. It was then divided into three sections representing different components controlling spring discharge. The division criteria were not determined solely by visual assessment, but were based on the FDC and defined as the probable percentage-of-time range corresponding to a given discharge. For the three-component MRC separation, two percentage ranges were specified. The software tested successive separation variants at 1% increments and selected the scenario with the highest average coefficient of determination, R^2 (Posavec *et al*. 2010).

Knowledge of the recession coefficient α allows the volume of water stored in the groundwater reservoir to be estimated for any spring-discharge value (Castany 1968; Korkmaz 1990), representing the so-called dynamic reserve, W (Equation 1). In this study, W denotes the estimated dynamic reserve of stored groundwater associated with spring recession. In this context, W represents neither the total volume of groundwater stored in the reservoir nor the geometrically defined storage capacity of the entire aquifer system. For all springs, the mean dynamic groundwater storage associated with spring recession W_{mean} was determined using the mean discharge from the multi-year period (Q_{mean}):

$$W_{mean} = \frac{86400 \cdot Q_{mean}}{\alpha} \qquad [1]$$

where: W_{mean} – mean dynamic groundwater storage associated with spring recession (dynamic reserve) [m^3], Q_{mean} – mean spring discharge [m^3/s], α – recession coefficient [1/d].

In the next step, the groundwater renewal rate of the active exchange zone was calculated using the renewal coefficient η (Equation 2) (Tomalski and Tomaszewski 2015).

$$\eta = \frac{VZR}{W_{mean}} \qquad [2]$$

where: η – renewal coefficient, VZR – mean annual spring discharge total [m^3].

The coefficient η, derived from the ratio of VZR to the estimated mean dynamic storage, W_{mean}, should not be interpreted as indicating the complete replacement of water within the reservoir or the actual residence time, as the calculation excludes the hydraulically inactive portion of the groundwater resources.

Using the determined recession coefficient α values based on the MRCs, the mean hydraulic conductivity k (Equation 3) of the rocks storing and conducting groundwater drained by the described springs was also determined (Kowalski 1984). The term 'mean' was adopted because the k value reflects the integrated behaviour of the entire spring system and should not be regarded as equivalent to a point-specific hydraulic conductivity value obtained from pumping tests or laboratory investigations.

$$W_{mean} = \frac{\alpha}{0.000469} \qquad [3]$$

where: k – hydraulic conductivity [m/d]

According to an experiment conducted by Kowalski (1984), in accordance with the Dupuit equation, the hydraulic gradient does not affect the change of the recession coefficient α, but determines the magnitude of the discharge. Thus, a change in the thickness of the saturation zone and the length of the groundwater flow path does not affect the change in the rate of the spring discharge recession process (α is constant). Furthermore, there is evidence to suggest that the recession coefficient is significantly correlated with hydraulic conductivity ($r > 0.9$). This relationship is described by Equation 4:

$$\alpha = 4.69 \cdot 10^{-4} k, \quad r > 0.9 \qquad [4]$$

Kowalski's empirical relationship was derived for specific laboratory conditions and should therefore be used with caution when comparing different lithologies, including sandstones, granites, crystalline schists, tuffs and tuffites. In addition, as the discharge data are available at a weekly time step, short-duration maxima and the earliest stages of recession may not have been captured, especially in unstable springs characterized by high discharge variability. Consequently, parameters calculated on the basis of α values should be regarded as indicative

and comparative measures, rather than precise hydrogeological parameters of individual aquifer systems.

In the final stage of the study, the baseflow components of spring discharge were determined by hydrograph separation, and baseflow indices (BFI) were calculated. For this purpose, the web tool SepHydro was used (Danielescu *et al*. 2018), developed through a collaborative research effort between the Canadian Rivers Institute (CRI), the University of New Brunswick (UNB), Agriculture and Agri-Food Canada (AAFC) and Environment and Climate Change Canada (ECCC). This tool uses digital filtering methods. The Lyne and Hollick (1979) method was selected, although its application to springs requires a different interpretation from that commonly adopted for rivers. In classical hydrology, the Lyne-Hollick filter is used primarily to separate a river-flow hydrograph into baseflow and direct runoff. For springs, however, the interpretation is slightly different, as total spring discharge is treated as a hydrological signal comprising a slowly varying component, referred to as the baseflow component of spring discharge, which reflects the sustained recharge of the groundwater reservoir, and a rapidly varying component associated with the short-term response of the spring system to infiltration recharge (Ladson *et al*. 2013; Bailly-Comte *et al.* 2023). In spring-discharge studies, the filter is particularly useful when the objective is to quantify the contribution of stable groundwater recharge to total discharge and to distinguish episodes of rapid response following rainfall or snowmelt events (Giese *et al.* 2025). It should be stressed, however, that the separation result is model-based and operational, rather than directly physical, because the digital filter does not incorporate geological structure, aquifer hydraulic parameters or the actual groundwater flow time. Thus, the BFI represents the proportion of stable groundwater recharge in total spring discharge. In dynamic springs, this value may be under- or overestimated owing to the weekly resolution of the data and the selection of filter parameters; therefore, the results were treated as comparative indicators.

RESULTS AND DISCUSSION

To provide a clear structure for the presentation and interpretation of the results, the 'Results and Discussion' section was divided into subsections focusing on spring-discharge stability, spring seasonality and response to precipitation, the aquifer memory effect, groundwater exchange, and relative drainage stability and susceptibility to low-flow conditions.

Spring-discharge stability

All springs covered by this study are characterized by continuous natural groundwater outflow. Statistical analysis of spring discharge indicates that Szczytna spring has the highest discharge and the greatest stability (Table 3). By far the lowest mean discharges (0.26–0.27 L/s) were recorded at the Kowary and Różanka springs, which drain weathering mantles and a fractured crystalline rock mass. Despite the very similar discharges of both springs, Różanka spring is more stable (Table 3). Kowalowa spring is characterized by the highest discharge variability. The high SCVP value may reflect the relatively rapid response of the near-surface groundwater system drained by this spring to rainfall and snowmelt. Analyses of spring discharge in the Sudetes indicate that springs fed by fractured and weathered media are generally more variable than those associated with porous, porous-fractured or large karst systems (Bartnik and Moniewski 2019). In areas underlain by crystalline rocks, higher discharge variability suggests the dominance of fracture flow, high hydraulic conductivity and limited storage capacity. In contrast, in compact sedimentary rocks, such as sandstones and marls, groundwater outflow is more diffuse, resulting in lower spring-discharge variability (Buczyński 2018).

In addition, FDCs were used to assess discharge variability and to provide insight into the frequency and duration of low spring-discharge conditions. The FDCs are presented in Text-fig. 3, while the calculated discharge indices are given in Table 4.

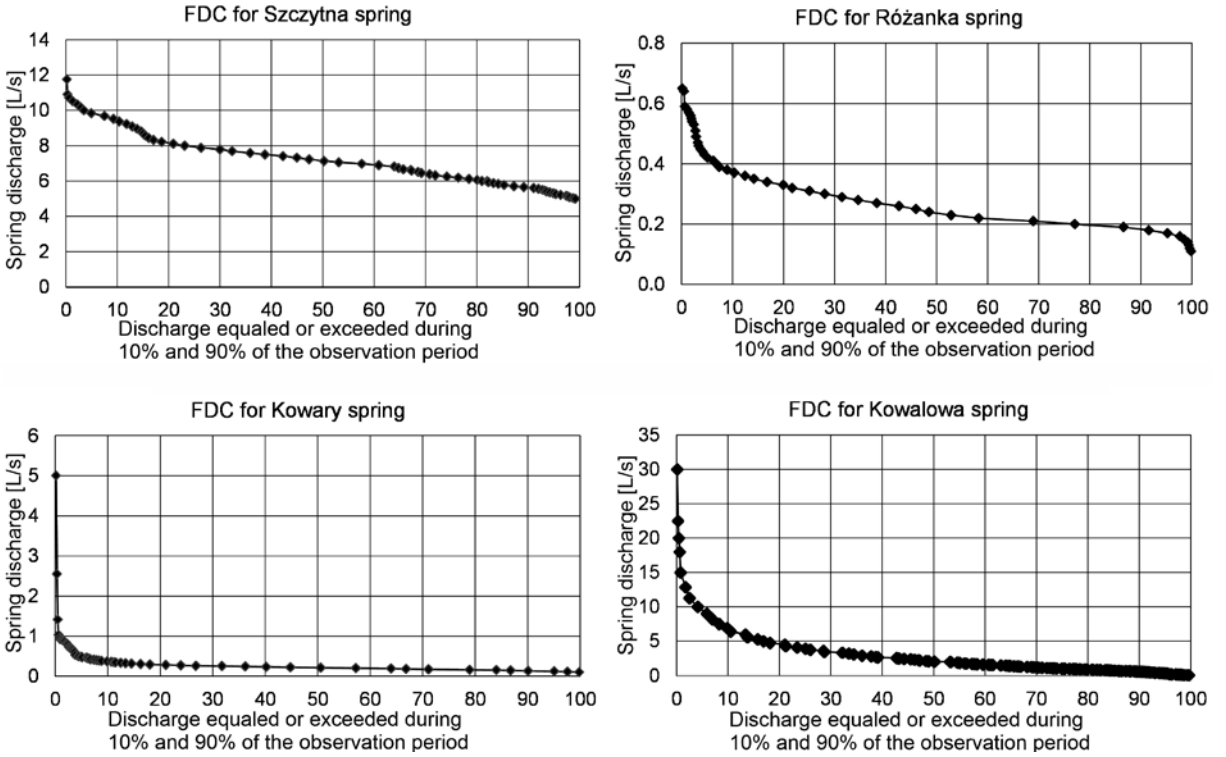
The variability range of spring discharge indices is as follows: Q10/Q90 from 1.67 to 11.53, Q90/

Spring	Q_{min} [L/s]	Q_{max} [L/s]	Q_{mean} [L/s]	Q_{sd} [L/s]	SCVP [%]
Szczytna	5	11.76	7.31	1.35	18 (low)
Kowary	0.1	5	0.26	0.25	96 (moderate)
Kowalowa	0.07	30	3.14	3.27	104 (high)
Różanka	0.11	0.65	0.27	0.09	33 (low)

Table 3. Discharge variability parameters of springs. Q_{min} – lowest discharge; Q_{max} – highest discharge; Q_{avg} – mean discharge; Q_{sd} – discharge standard deviation; SCVP – spring coefficient of variation parameter.

Spring	Q10	Q30	Q50	Q90	Q10/ Q90	Q90/ Q50	Q50/ Q90
Szczytna	9.38	7.79	7.14	5.61	1.67	0.78	1.27
Kowary	0.7	0.25	0.21	0.13	5.38	0.62	1.61
Kowalowa	6.92	3.33	2.09	0.6	11.53	0.29	3.48
Różanka	0.37	0.29	0.23	0.18	2.05	0.78	1.28

Table 4. Low-flow indices based on FDCs obtained for the investigated springs. Q10: 10th percentile; Q30: 30th percentile; Q50: 50th percentile; Q90: 90th percentile.



Text-fig. 3. Flow duration curves (FDCs) of the investigated springs.

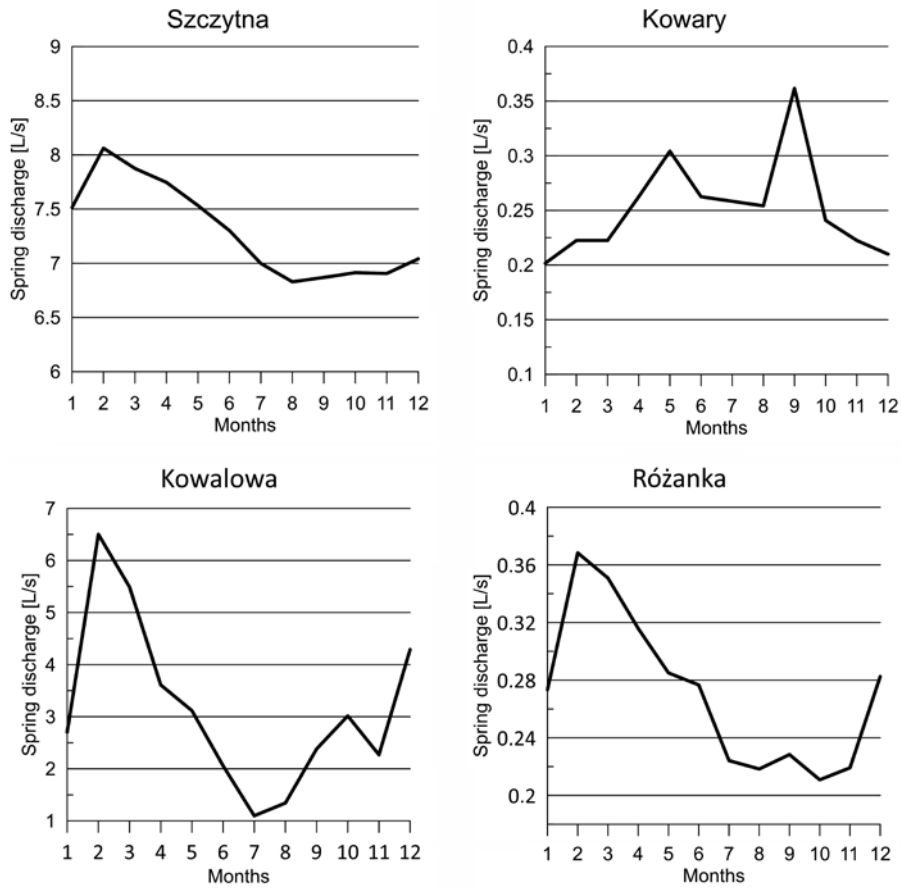
Q50 from 0.29 to 0.78, and Q50/Q90 from 1.27 to 3.48 (Table 4). Kowalowa spring has a high Q10/Q90 ratio compared to the other springs. A higher Q10/Q90 ratio means that discharges are highly variable and there is a possibility of very low spring discharge during low-flow periods. Kowalowa shows the highest Q10/Q90 value, confirming the greatest amplitude and the highest risk of very low discharge under low-flow conditions. The analysis of discharge indices highlights a clear contrast between Szczytna spring, which is associated with more capacious sedimentary aquifer rocks, and springs drained by fast, shallow fracture-weathering systems.

Spring seasonality and response to precipitation

Based on long-term mean monthly spring-discharge data for the period 2014–2025, most of the analysed springs, with the exception of Kowary, showed their highest discharges in February and March, and their lowest values in summer, in July and August (Text-fig. 4). This pattern is commonly observed in the Sudetes. Discharge maxima are associated with the infiltration of snowmelt water and limited evapotranspiration, whereas minima result from insufficient replenishment of water resources and high evapotranspiration (Bartnik and Moniewski 2019). These results indicate that summer precipitation does not always translate directly into an increase in spring discharge.

The late winter to spring period, from February to April, is the main snowmelt period in the elevation zone where the springs described in this study are located. During this period, recharge of shallow aquifers usually increases, leading to higher spring discharge, particularly in fractured and weathered rocks (Urban *et al.* 2023). In the Sudetes, groundwater resources recharged during the winter-spring period, together with occasional early-summer precipitation, sustain spring discharge for a considerable part of the season before the onset of the autumn hydrogeological low-flow period (Buczyński 2018).

The influence of snowmelt on springs is stronger and more rapid in crystalline rocks, weathered covers and fracture zones, where flow occurs through shallow, highly conductive pathways with relatively low storage capacity. In catchments composed of sandstones and marls, groundwater flow is more diffuse, resulting in lower seasonal variability of spring discharge; under such conditions, the snowmelt effect is more attenuated and extended over time (Buczyński 2018).

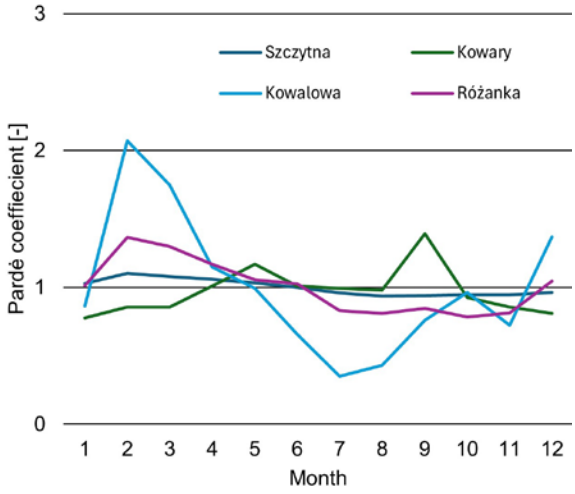


Text-fig. 4. Mean monthly discharges of springs from 2014 – 2025.

Seasonality is further supported by the Pardé coefficient values, which range from 0.8 to 1.4 for Kowary, Kowalowa and Różanka (Text-fig. 5). By contrast, in Szczytna, where the coefficient values oscillate around 1, seasonality is relatively weak and strongly attenuated by the storage properties of the aquifer. Nevertheless, Text-fig. 4 indicates the occurrence of an early-spring maximum and a summer-autumn minimum.

Kowalowa spring also exhibits a pronounced increase in discharge during the winter-spring period, followed by a decline in summer (Text-figs 4 and 5). This summer decrease suggests that the shallow system has a limited capacity to sustain outflow under reduced effective recharge conditions. In terms of resilience to hydrogeological drought, Kowalowa therefore represents the system most vulnerable to rapid depletion of groundwater resources.

Cross-correlation analysis between monthly precipitation totals and spring discharge shows that the simple precipitation-discharge relationship is weak and does not allow for more detailed process-based interpretation. Although the highest monthly precipitation totals occur in summer, spring-discharge maxima are observed in winter or early spring. This suggests that monthly precipitation is not the sole variable controlling discharge magnitude. Snow

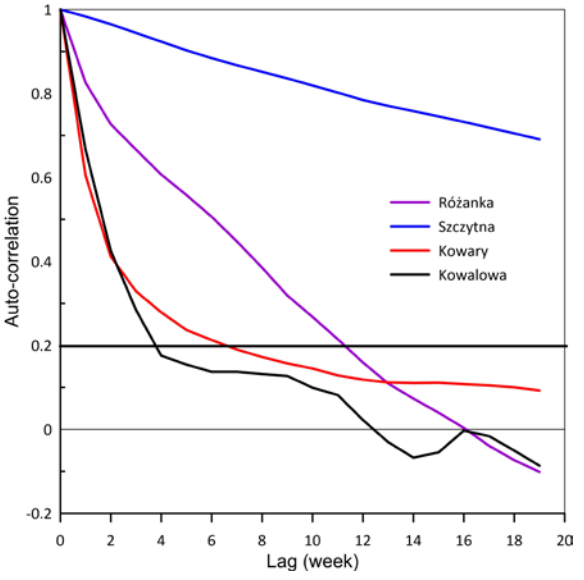


Text-fig. 5. Pardé coefficients.

storage, evapotranspiration, and the storage capacity of the rock medium also play a major role; however, hydrographs alone cannot be used to quantify the contribution of each factor. The highest CCF value was recorded for Kowary (0.48 at a lag of 0 months); however, the rapid decrease in correlation at the next lag, to values ranging from −0.2 to 0.2, indicates that this relationship has limited interpretative significance. Because the analysed time series were autocorrelated, the value of r = 0,48 was not interpreted as statistically independent evidence of the system's response to recharge. Therefore, CCF should be regarded as a supplementary analysis rather than a basis for drawing conclusions about recharge mechanisms.

The aquifer memory effect

To determine the aquifer memory effect, the autocorrelation function (ACF) was used. The autocorrelogram describes how long current discharge values remain statistically dependent on preceding values (Text-fig. 6). In this sense, the ACF is an indicator of hydrograph memory, which may reflect water retention and the mode of water release, but it does not, on its own, allow the actual residence time of water or the geometry of rock voids to be determined. As studies by Larocque *et al.* (1998) show that the most rapidly decreasing autocorrelation of springs may be associated with larger fractures with a wider network of groundwater flow paths and the presence of larger pore spaces. On the other hand, a relatively larger aquifer memory effect can be associated with smaller fractures with a narrower drainage network and smaller pore spaces. However, any interpretation of fracture characteristics, porosity and flow pathways remains indirect and should be regarded as an interpretative hypothesis. It requires confirmation through detailed hydrochemical and isotopic investigations, or by means of hydrogeological modelling.



Text-fig. 6. Auto-correlation calculation (ACF) of the springs in the study area.

The highest ACF at lag 1 (= 7 days) was recorded for the Szczytna (0.98) and Różanka (0.82) springs, while the lowest ACF in the range of 0.55–0.66 was recorded for the remaining 2 springs. Szczytna and Różanka springs are characterized by more slowly declining autocorrelograms (Text-fig. 6), which indicates greater hydrograph inertia and a more gradual release of water from the reservoir. The positive memory effect is approximately 12 weeks for Różanka, while in Szczytna the autocorrelation coefficient did not decrease below 0.2 within the analysed 19-week lag period. In Kowalowa, the value r(k) = 0.2 is reached after approximately 4 weeks, confirming the most dynamic behaviour of this system. Kowary occupies an intermediate position, with a memory effect of approximately 7 weeks. These differences are consistent with a conceptual model in which the Cretaceous reservoir has the highest storage capacity, whereas the shallow system developed in weathered volcanogenic rocks responds most rapidly to recharge.

As noted in the methodological section, the term 'memory effect' denotes a statistical property of the discharge time series and is not directly equivalent to the actual residence time of water within the reservoir. Groundwater associated with weathered zones and fractured rock masses of metamorphic, magmatic or volcanic rocks in the Sudetes should be regarded mainly as young water involved in active circulation, with residence times ranging from months to several years. In the deeper parts of the weathered-fractured profile and in valley drainage zones, components with residence times of several decades may also occur. This range is consistent with the model of groundwater circulation in the crystalline rocks of the Sudetes and with the results of isotopic and hydrogeochemical studies conducted in analogous mountainous areas of Central Europe, such as the Izera Mountains, the Black Forest and the Vosges (Staśko and Tarka 2002; Chabaux *et al*. 2017; Jankovec *et al.* 2017; Lachassagne *et al*. 2021). Much longer groundwater circulation times are recorded in the Cretaceous sedimentary rocks of the Sudetes, i.e. the hydrogeological setting of the Szczytna spring. Shallow fracture-porous systems are recharged un-

der present-day conditions and contain waters with circulation times of the order of several to several tens of years, whereas deeper, partly isolated aquifers may contain components several hundred years old. In deep confined aquifers, by analogy with the Czech Cretaceous Basin, old waters ranging in age from several hundred years to more than 20 ka may occur (Kadlecova *et al.* 2008; Corcho Alvarado *et al.* 2013; Bruthans *et al*. 2026). Groundwater circulation times in the different rock environments of the Sudetes and other mountainous regions of Central Europe are therefore substantially longer than those suggested by the ACF results, meaning that the latter should not be interpreted as direct measures of groundwater residence time within the reservoir.

Groundwater exchange

MRCs allow the depletion rates of the drained aquifer systems to be compared (Text-fig. 7; Table 5). The recession curves of the investigated springs have the most clearly developed early recession segments, especially for Kowalowa and Kowary, whereas the intermediate and late segments are less well defined. This suggests that the rapid drainage component is of considerable importance in these systems, while the slower recession phases should be interpreted with caution.

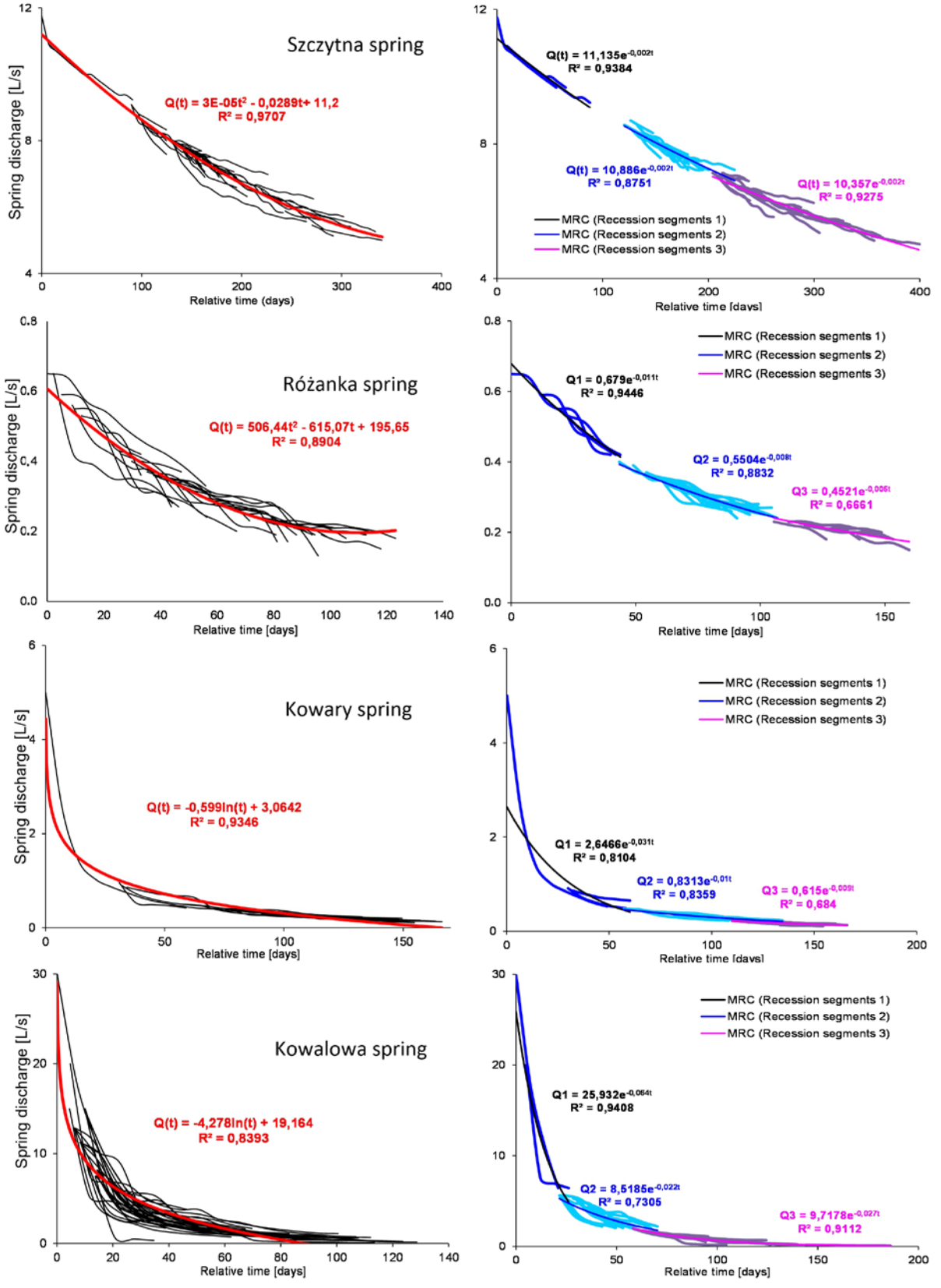
Szczytna represents the system characterized by the slowest drainage and the highest groundwater storage capacity (Table 5). In absolute terms, however, this result probably reflects not only lithological properties, but also a larger recharge area and the contribution of deeper groundwater circulation. Kowary and Różanka display similar values for the late recession segments, suggesting a comparable contribution of the slow drainage component in shallow weathered-fractured systems. Kowalowa has the highest recession coefficients, confirming rapid depletion of the shallow aquifer system and a lower capacity to maintain discharge during periods of recharge deficit.

The W_{mean} values (Table 5) indicate that the Cretaceous aquifer system drained by the Szczytna spring has the greatest storage potential among the analysed systems. This is consistent with the hydrogeological setting of the area, where the aquifer thickness exceeds 100 m and recharge may involve both shallow and deeper groundwater circulation systems (Tarka 2006). For Szczytna, the estimated volume of stored groundwater was approximately 300,000 m³, whereas local shallow aquifer systems developed in weathered and highly fractured crystalline rocks, and in sedimentary rocks of volcanogenic origin, show values below 10,000 m³ (Table 5). Because the recharge-area extent was not determined in this study, and no such information is available in the literature, it remains unclear how much of the observed variation in W_{mean} is attributable to contrasting aquifer properties and how much simply reflects differences in the size of the aquifer system. The longer observation period (2014–2025) considered in the present study broadly confirms the contrast between Szczytna and Różanka described by Olichwer (2023), while also refining the earlier interpretation. In the previous study, covering the period 2014–2021, the values obtained for Szczytna and Różanka were 264,319 m³ and 1,918 m³, respectively. In the present analysis of segmented MRCs, the corresponding values were approximately 300,754 m³ and 2,777 m³. Despite differences in the study period and the method used to analyse recession, the similar ranking of the two springs supports the validity of a comparative interpretation. However, the shifts in the numerical values demonstrate the sensitivity of the results to model specification and the length of the observation period, and argue against treating these estimates as precisely determined physical properties of the aquifer systems.

Consistent with the highest α_{mean} value, the Kowalowa spring is characterized by the shortest exchange time of the mean storage potential, at approximately 3.8 weeks. The ACF and recession-derived results (η and 52/η) are qualitatively consistent; however, they should not be interpreted as equivalent parameters of water residence time within the reservoir. Verification of actual groundwater circulation times would require independent isotopic, hydrochemical or tracer data.

Spring	Master recession coefficient (α)			α_{mean}	k [m/d]	W_{mean} [m³]	η	52/η
	First seg.	Second seg.	Third seg.					
Szczytna	0.0023	0.0021	0.0019	0.0021	4.5	300,754	0.76	68
Kowary	0.031	0.0103	0.0094	0.0169	36	1,329	6.16	8.4
Kowalowa	0.0636	0.0222	0.0271	0.0377	80.4	7,196	13.77	3.8
Różanka	0.0113	0.0078	0.006	0.0084	17.9	2,777	3.06	17

Table 5. Recession parameters based on separated MRCs. $\alpha_{mean,}$ – mean recession coefficient; W_{mean}, – mean dynamic groundwater storage associated with spring recession; η – renewal coefficient [1/year]; 52/ η – estimated renewal time in weeks, k – hydraulic conductivity.



Text-fig. 7. Master recession curves and MRCs optimally separated into three segments for the investigated springs.

The hydraulic conductivity values derived from the empirical relationship with the recession coefficient for the aquifer systems described here span almost two orders of magnitude, ranging from 4.5 to 80.4 m/d (Table 5). For the Szczytna, Różanka and Kowary sites, the estimated hydraulic conductivity values are broadly consistent with published values for comparable lithologies. Laboratory studies of Cretaceous sediments in the Sudetes (Tarka 2006) showed that the geometric mean k value for sandstones is 3.08 m/d. In addition, in the Sudetes, test-pumping results from boreholes located within zones of weathered and fractured gneisses yielded k values ranging from 0.2 to 14.7 m/d (Staśko and Tarka 2002). Field studies of hydraulic conductivity based on fracture measurements indicated a k range of 0.01 to 32.8 m/d for gneisses (Szczepanowski and Staśko 2001). In the case of metamorphic rocks in the vicinity of Różanka, recession analysis gives k values within the upper range of those reported in the literature. For granitoid rocks and their weathering covers in south-western Poland, hydraulic conductivity values are highly variable, being controlled mainly by the degree of weathering, the proportion of clay fraction, granite fracturing, the presence of debris material and the method of determination. Laboratory studies of granite weathering covers showed k values ranging from 0.7 to 71.5 m/d, with a mean of 13.02 m/d (Górecka and Marszałek 2013). By contrast, for the Kowalowa spring, the hydraulic conductivity value derived from the empirical relationship with the recession coefficient is rather uncertain. Owing to the lack of literature data, it is difficult to assess and verify the obtained k value. Volcanic rocks in the Sudetes constitute a highly heterogeneous medium. In their compact state, their permeability may be low, whereas after weathering, loosening and fracturing it may increase by several orders of magnitude. A wide range of k values can therefore be expected. It should be recalled that the k values obtained from recession analysis represent average values for the entire system drained by the spring, whereas literature data are point-specific and refer to particular locations. The resulting k values are subject to unquantified uncertainty and should therefore be regarded only as order-of-magnitude estimates. The transferability of recession-analysis-derived k values is expected to be lowest in highly heterogeneous, weathered and fractured volcanogenic media, in which the geometry and connectivity of preferential flow paths differ substantially from the conditions represented in Kowalski's (1984) original experiment. In summary, the parameters presented in Table 5 and calculated from the α values should be treated as indicative and comparative measures rather than as accurate hydrogeological parameters of the individual aquifer systems.

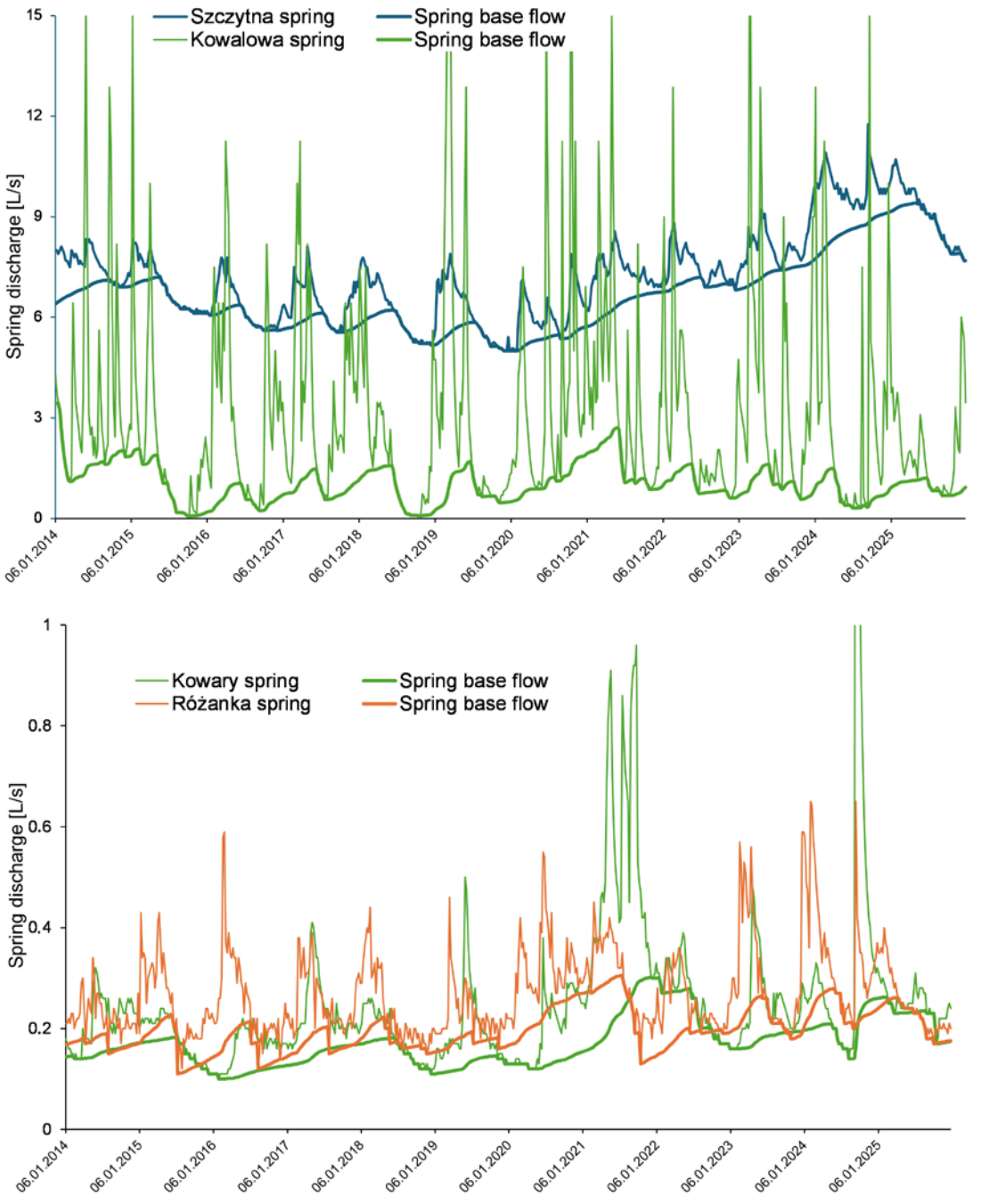
Relative drainage stability and susceptibility to low-flow conditions

The hydrograph separation results and BFI values (Text-fig. 8; Table 6) should be interpreted as indicators of the relative stability of drainage and are broadly consistent with the previously analysed indices of spring dynamics. The consistency between the high BFI, flat FDC, long ACF memory and low recession coefficients observed at Szczytna strengthens the interpretation of gradual aquifer drainage. In contrast, the low BFI, steep FDC, short ACF memory and high recession coefficients at Kowalowa consistently point to a highly dynamic discharge response. The intermediate and partly contrasting results for Kowary and Różanka show that lithology alone cannot adequately explain the observed differences, as the indicator values are also affected by recharge-area size, spring discharge, fracture-network connectivity and measurement resolution.

The Q90/Q50 coefficient values (Table 4), together with high BFI values (Table 6), confirm that the Szczytna, Różanka and Kowary springs have a substantial baseflow contribution to total discharge. Szczytna, which has the highest mean and median discharge (Q50), the lowest SCVP value (Tabs 3 and 4), and a flat FDC (Text-fig. 3), drains the largest aquifer reservoir, characterized by gradual groundwater release. In contrast, the least stable groundwater system is represented by the weathered volcanic rocks drained by the Kowalowa spring, as indicated by the steep FDC slope, unstable discharge conditions and the lowest BFI value. The rapid depletion of this shallow aquifer system increases the vulnerability of the Kowalowa spring to drought periods. Kowary and Różanka, with BFI values of 67–73% (Table 6), indicate intermediate resilience of shallow weathered-fractured systems.

Spring	b_{min}	b_{max}	b_{mean}	Q_{mean}	BFI
	[L/s]				%
Szczytna	5	9.41	6.65	7.31	91.1
Kowary	0.1	0.3	0.17	0.26	66.7
Kowalowa	0.07	3.44	1.02	3.14	32.5
Różanka	0.11	0.3	0.19	0.27	72.5

Table 6. Base spring discharge parameters based on hydrograph separation. b_{min} – min. base spring discharge; b_{max} – max. base spring discharge; b_{mean} – mean base spring discharge; Q_{mean} – mean discharge; BFI – baseflow index.



Text-fig. 8. Separated baseflow hydrographs of the investigated springs.

SUMMARY

In this study, classical methods of spring-discharge analysis were used for a process-based interpretation of the functioning of local groundwater systems in the Sudetes. The combined use of SCVP, FDC, ACF, MRC and BFI made it possible to assess not only discharge variability, but also relative storage, the rate of resource depletion and the susceptibility of the systems to periods of reduced recharge.

Three local models of aquifer-system functioning were analysed. The first, represented by Szczytna, comprises a porous-fractured Cretaceous reservoir with a contribution from deeper circulation and the

greatest storage capacity. The second, represented by Kowary and Różanka, corresponds to shallow weathered-fractured systems developed in crystalline rocks, with intermediate drainage stability. The third, represented by Kowalowa, is a shallow and dynamic system associated with weathered volcanogenic rocks. These local conceptual models should not be regarded as a statistically validated classification of all mountain aquifer systems.

The most stable discharge, the longest statistical memory effect and the greatest storage potential were identified in Szczytna. Kowary and Różanka show smaller water resources and a shorter hydrograph memory, but still retain the capacity to maintain relatively stable discharge. Kowalowa shows the greatest discharge variability, a distinct winter-spring response, the highest recession coefficients and the shortest exchange time of the mean storage potential. From a process-based perspective, this is the system most susceptible to rapid depletion of water resources and potentially the least resilient to prolonged periods of hydrogeological drought.

The results obtained are primarily of regional and applied significance. They do not constitute a new classification of mountain groundwater systems, but demonstrate that long-term spring-discharge measurement series can be useful for preliminary, process-based recognition of storage and drainage conditions. The results presented in this study should be treated as comparative and indicative. First, only four springs were analysed; therefore, the influence of lithology cannot be fully separated from local factors such as the size of the recharge area, elevation, slope inclination, snow conditions and the geometry of fracture zones. Second, the weekly measurement interval may fail to capture short-duration high-flow events and the early stages of recession, which is particularly important for the dynamic Kowalowa spring. Third, the lack of independently determined recharge areas and independent permeability measurements limits the possibility of interpreting W_{mean} and k as absolute hydrogeological parameters. Despite these limitations, the consistency between the FDC, ACF and MRC results suggests that spring-discharge data may serve as a useful first-order tool for assessing storage and drainage processes in poorly investigated mountain aquifer systems.

Acknowledgements

I would like to thank the anonymous reviewers for their careful evaluation of the manuscript and their constructive comments. Their reviews helped to improve the structure, methodological transparency, and scientific interpretation of the study.

REFERENCES

Amit, H., Lyakhovsky, V., Katz, A., Starinsky, A. and Burg, A. 2002. Interpretation of spring recession curves. *Groundwater*, **40** (5), 543.

Bailly-Comte, V., Ladouche, B., Charlier, J.B., Hakoun, V. and Maréchal, J.C. 2023. XLKarst, an Excel tool for time series analysis, spring recession curve analysis and classification of karst aquifers. *Hydrogeology Journal*, **31**, 2401–2415.

Bartnik, A. and Moniewski, P. 2019. Multiannual variability of spring discharge in Southern Poland. *Episodes*, **42** (3), 187–198.

Bocheńska, T., Wąsik M. and Marszałek, H. 2002. Karstic aquifers in crystalline formation of Sudety Mts. Acta Universitatis Wratislaviensis – Hydrogeology, No 2460, 66 pp. University of Wrocław; Wrocław. [In Polish with English summary]

Bonacci, O. 1993. Karst springs hydrographs as indicators of karst aquifers. *Hydrological Sciences Journal*, **38**, 51–62.

Bruthans, J., Slavík, M., Mareš, J., Šabatová, K., Kůrková, I. and Nol, O. 2026. Re-Evaluation of Groundwater Flow Systems in Sedimentary Basin Based on Wide Range of Environmental Tracers, Hydrostratigraphy, and Field Measurements. *Water*, **18** (6), 683.

Buczyński, S., Modelska, M., Olichwer, T., Tarka, R. and Staśko, S. 2011. Spring hydrogeology of mountainous areas of Kłodzko Region on the basis "Źródło" database. *Biuletyn Państwowego Instytutu Geologicznego*, **445**, 17–26. [In Polish with English summary]

Buczyński, S. 2018. Temporal variability of springs in catchment areas located in the Sudeten Mountains. *Hydrology Research*, **49** (3), 780–793.

Castany, G. 1968. Prospection et Exploitation des Eaux Souterraines (Prospecting and Exploitation of Groundwater), 718 pp. Dunod; Paris.

Chabaux, F., Viville, D., Lucas, Y., Ackerer, J., Ranchoux, C., Bosia, C., Pierret, M.C., Labasque, T., Aquilina, L., Wyns, R., Lerouge, C., Dezaye, C. and Negrel, P. 2017. Geochemical tracing and modeling of surface and deep water-rock interactions in elementary granitic watersheds (Strengbach and Ringelbach CZOs, France). *Acta Geochimica*, **36**, 363–366.

Corcho Alvarado, J. A., Pačes, T. and Purtschert, R. 2013. Dating groundwater in the Bohemian Cretaceous Basin: Understanding tracer variations in the subsurface. *Applied Geochemistry*, **29**, 189–198.

Dadlez, R., Marek, S. and Pokorski, J. (eds) 2000. Geological Map of Poland without Cenozoic deposits at a scale of 1:1,000,000 [digital map]. Polish Geological Institute, Warsaw. Available at: [https://geologia.pgi.gov.pl/arcgis/home/web-map/viewer.html?useExisting=1&layers=5e22884a51b-046cebed031b9594e5246] [accessed 3 March 2026]. [In Polish]

Danielescu, S., MacQuarrie, K.T.B. and Popa, A, 2018. SEPHYDRO: A Customizable Online Tool for Hydrograph Separation. *Groundwater*, **56**, 589–593.

Fatoni, H., Kholis. A.N., Kurniawan, I.A., Haryono, E., Waskito, W.A., Cahyadi, A., Agniy, R.F. and Adji, T.N. 2024. Use of discharge variability, aquifer memory effect and recession curve analysis in several springs to characterize karst aquifers in the tropical area. *Geosciences Journal*, **28**. 925–939.

Giese, M., Caballero, Y., Hartmann, A. and Charlier, J.B. 2025. Trends in long-term hydrological data from European karst areas: insights for groundwater recharge evaluation, *Hydrology Earth System Sciences*, **29**, 3037–3054.

Górecka, J. M. and Marszałek, H. 2013. Evaluation of selected hydrogeological parameters of weathered granite in the Strzegom area (Lower Silesia). *Gospodarka Surowcami Mineralnymi – Mineral Resources Management*, **29** (2), 103–118. [In Polish with English summary]

Grzegorczyk, K. 2002. Explanation to the hydrogeological map of Poland – Main aquifer in 1:50000, sheet Kowary (832). Polish Geological Institute-National Research Institute; Warsaw. [In Polish]

Hayashi, M. 2020. Alpine Hydrogeology: The critical role of groundwater in sourcing the headwaters of the World. *Groundwater*, **58**, 498–510.

Jankovec, J., Vitvar, T., Šanda, M., Matsumoto, T. and Han, L.F. 2017. Groundwater recharge and residence times evaluated by isotopes of hydro gen and oxygen, noble gases and CFCs in a mountain catchment in the Jizera Mts., northern Czech Republic. *Geochemical Journal*, **51**, 423–437.

Kadlecová, R., Bruthans, J., Bůzek, F., Oster, H. and Zeman, O. 2008. Groundwater residence time and nitrate contamination in shallow aquifers formed in basin Cretaceous sedimentary fills. *Geoscience Research Reports*, **41**, 217–224. [In Czech with English summary]

Korkmaz, N. 1990. The estimation of groundwater recharge from spring hydrographs. *Hydrological Sciences Journal* **35** (2), 209–217.

Kowalski, S. 1983. Analysis of the hydrogeological regime of the Stołowe Mountain springs in terms of identifying water-bearing horizons. In: Bieniewski, J. and Kryza, J. (Eds), 2nd National Symposium – Contemporary Problems of Regional Hydrogeology, Lądek Zdrój (Poland), 13–16 October 1982, Proceedings, 50–58. University of Wrocław; Wrocław. [In Polish]

Kowalski, S. 1984. Regression of groundwater drainage in the light of laboratory studies of filtration parameters. *Technika Poszukiwań Geologicznych*, **3**, 11–19. [In Polish]

Krešić, N. 2010. Sustainability and management of springs. In: Krešić, N and Stevanović, Z. (Eds), Groundwater Hydrology of Springs: Engineering, Theory, Management and Sustainability, 1–29. Butterworth-Heinemann; Oxford.

Kryza, H. and Kryza, J. 1983. Hydrogeological role of granite weathering cover on the example of the upper Kamienica River basin. In: Bieniewski, J. and Kryza, J. (Eds), 2nd National Symposium – Contemporary Problems of Regional Hydrogeology, Lądek Zdrój (Poland), 13–16 October 1982, Proceedings, 78–89. University of Wrocław; Wrocław. [In Polish]

Kryza, H. and Tarka, R. 1992. Groundwater in erlanic rocks of Śnieżnik Massif. In: Kowalski, J., Bocheńska, T., Ciężkowski, W., Kozerski, B., Krasny, J., Macioszczyk, T., Malinowski, J., Pulina, M., Różkowski, A., Strzelecki, T. and Zuber, A. (Eds), Third National Symposium – Hydrogeological problems of south-west Poland, Pokrzywna (Poland), 10–12 September 1992, Proceedings, 51–59. Oficyna Wydawnicza Sudety; Wrocław. [In Polish with English summary]

Lachassagne, P., Dewandel, B. and Wyns, R. 2021. Review: Hydrogeology of weathered crystalline/hard-rock aquifers – guidelines for the operational survey and management of their groundwater resources. *Hydrogeology Journal*, **29**, 2561–2594.

Ladson, A. R., Brown, R., Neal, B. and Nathan, R. 2013. A standard approach to baseflow separation using the Lyne and Hollick filter. *Australian Journal of Water Resources*, **17** (1), 25–34.

Larocque, M., Mangin, A., Razack, M. and Banton, O. 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). *Journal of Hydrology*, **205** (3–4), 217–231.

Lyne, V. and Hollick, M. 1979. Stochastic time-variable rainfall-runoff modelling. In: Hydrology and Water Resources Symposium: Symposium Papers, Perth, 10–12 September 1979. Institution of Engineers Australia, Barton, Australia, National Conference Publication No. 79/10, 89–93.

Maillet, E.T. 1905. Essais d'Hydraulique Souterraine et Fluviale, 218 pp. A. Hermann; Paris.

Mangin, A. 1984. Pour une meilleure connaissance des systemes hydrologiques a partir des analyses correlatoire et spectrale. *Journal of Hydrology*, **67**, 25–43.

Marszałek, H. 1996. Hydrogeology of the upper part of the Kamienna river catchment in the West Sudetes. Geological and Mineralogical Papers, 54, 102 pp. University of Wrocław, Wrocław. [In Polish with English summary]

Mayaud, C., Wagner, T., Benischke, R. and Birk, S. 2014. Single event time series analysis in a binary Karst catchment evaluated using a groundwater model (Lurbach system, Austria). *Journal of Hydrology*, **511**, 628–639.

Mazur, S., Aleksandrowski, P., Turniak, K. and Awdankiewicz, M. 2007. Geology, tectonic evolution and Late Paleozoic magmatism of Sudetes – an overview. In: Kozłowski, A. and Wiszniewska, J. (Eds), Granitoids in Poland, 59–87. AM Monograph No. I. Faculty of Geology of the Warsaw University; Warszawa.

Meinzer, O. E. 1923. The occurrence of ground water in the United States, 489 pp. USGS Water Supply paper. United States government printing office; Washington.

Nathan, R.J. and McMahon, T.A. 1990. Evaluation of automated techniques for base flow and recession analyses. *Water Resources Research*, **26**, 1465–1473.

Negi, G.C.S. and Joshi, V. 1996. Geo-hydrology of springs in a mountain watershed: the need for problem solving research. *Current Science*, **71** (10), 772–776.

Olichwer, T. 2023. Hydrogeological characterization of local groundwater reservoirs in the Kłodzko Land (Sudetes – SW Poland) based on an analysis of the discharges of springs. *Carpathian Journal of Earth and Environmental Sciences*, **18** (1), 171–182.

Posavec, K., Bacani, A. and Nakić, Z. 2006. A visual basic spreadsheet macro for recession curve analysis. *Groundwater*, **44**, 764–767.

Posavec, K., Parlov, J. and Nakić, Z. 2010. Fully automated objective-based method for master recession curve separation. *Groundwater*, **48** (4), 598–603.

Posavec, K., Giacopetti. M., Birk, S. and Materazzi, M. 2017. Method and excel VBA algorithm for modeling master recession curve using trigonometry approach. *Groundwater*, **55** (6), 891–898.

Seelig, M., Seelig, S., Vremec, M., Wagner, T., Brielmann, H., Eybl, J. and Winkle., G. 2024. Quantitative Classification of Spring Discharge Patterns: A Cluster Analysis Approach. *Hydrological Processes*, **38**, e15326.

Springer, A.E., Stevens, L.E., Anderson, D.E., Parnell, R.A., Kreamer, D.K. and Flora, S.P. 2004. A comprehensive springs classification system: integrating geomorphological, hydrogeochemical and ecological criteria. In: Stevens, L.E. and Meretsky, V.J. (Eds.), Aridland Springs in North America: Ecology and Conservation, 49–75. University of Arizona Press and the Arizona-Sonora Desert Museum; Tucson.

Staśko, S. and Tarka, R. 2002. Groundwater recharge and drainage processes in mountainous terrains based on research in the Snieznik Massif. Acta Universitatis Wratislaviensis No 2528, 66 pp. University of Wrocław Publishing; Wrocław. [In Polish with English summary]

Staśko, S., Tarka, R., Olichwer T. and Lubczyński M.W. 2010. Groundwater recharge in mountainous terrains – case study from Sudeten Mountains in SW Poland. In: Paliwal, B.S. (Eds), Global groundwater resources and management, 451–474. Scientific Publishers; Jodhpur.

Staśko, S. and Buczyński, S. 2018. Drought and its effects on spring discharge regimes in Poland and Germany during the 2015 drought, *Hydrological Sciences Journal*, **63** (5), 741–751.

Szczepanowski, S. and Staśko, S. 2001. Hydraulic conductivity of rocks in Śnieżnik Massif based on fractures measurements. *Contemporary Problems of Hydrogeology*, 10 (1), 263–270. [In Polish with English summary]

Tallaksen, L. M. 1995. A review of base flow recession analysis. *Journal of Hydrology*, **165** (1–4), 349–370.

Tarka, R. 2006. Hydrogeological characteristics of Cretaceous formations in the Polish part of the Sudetes. Acta Universitatis Wratislaviensis – Hydrogeology, No 2884, 117 pp. University of Wrocław; Wrocław. [In Polish with English summary]

Toebes, C., Morrissey, W. B., Shorter, R. and Hendy, M. 1969. Base flow recession curves. In: Handbook of Hydrological Procedures, Procedure No. 8, 10 pp. Ministry of Works; Wellington.

Tomalski, P. and Tomaszewski, E. 2015. Methods, formulas and calculation formulas used in the work. In: Jokiel, P. (Eds), Statistical methods in hydrological analyses of central Poland, 215–271. University of Łódź; Łódź. [In Polish]

Tomczyk, A.M. and Bednorz, E. 2022. Climate atlas of Poland (1991–2020). Wydawnictwo Naukowe; Poznań. [In Polish]

Urban, G., Richterova, D., Kliegrova, S. and Zuskova, I. 2023. Reasons for shortening snow cover duration in the Western Sudetes in light of global climate change. *International Journal of Climatology*, **43** (12), 5485–5511.

Vogel, R. M. and Fennessey, N. M. 1995. Flow duration curves II: A review of applications in water resources planning. *Journal of the American Water Resources Association*, **31** (6), 1029–1039.

Weingartner, R., Blöschl, G., Hannah, D.M., Marks, D.G., Parajka, J., Pearson, C.S., Rogger, M., Salinas, J.L., Sauquet, E., Srikanthan, R., Thompson, S.E. and Viglione, A. 2013. Prediction of seasonal runoff in ungauged basins. In: Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A and Savenije, H. (Eds), Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales, 102–134. Cambridge University Press; Cambridge.

Wojtkowiak, A. 2002. Explanation to the hydrogeological map of Poland – Main aquifer in 1:50000, sheet Kamienna Góra (833). Polish Geological Institute-National Research Institute; Warsaw. [In Polish]

Manuscript submitted: 8th April 2026
Revised version accepted: 13th October 2026