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Groundwater capacity of a flysch-type aquifer feeding springs in the Outer Eastern Carpathians (Poland)

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ABSTRACT

The aim of the study is to assess the capacity of the flysch aquifer feeding springs in the Outer Eastern Carpathians using spring recession curves. The four selected springs are located in an area generally believed to be poor in groundwater. However, the selected springs were characterized by remarkably high average discharge of 3.2–9.6 L s^{-1}. Recession coefficients were estimated which enabled an aquifer capacity and groundwater residence time assessment. Despite similarities in elevation, precipitation, and lithology in the study area, a substantial variation in the recession coefficients and aquifer parameters was found. The average aquifer capacity of groundwater subsystems strongly varied in the small study area (4.9–49 m$^3 \times 10^3$). The mean groundwater residence time varied from 11 days to 50 days depending on the volume of groundwater drained by the springs. Differences in discharge, recession coefficients, groundwater capacity, and residence time were related to recharge areas of different size. Simple relationships between the topographic catchment areas of springs and their hydrologic parameters can become altered by local structural features: faults and fissures. The study demonstrates that tectonically produced structures may facilitate a larger supply of groundwater and the occurrence of high-discharge springs in a given area.

Key words | flysch-type aquifer, recession curve, sedimentary rocks, spring recharge, tectonics

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INTRODUCTION

The flysch part of the Carpathians in southern Poland is characterized by low water storage. Large areas of the Carpathians in this region feature conditions that do not favor the collection of water capable of deep infiltration into bedrock (Łajczak 1996). In effect, this means that groundwater levels and spring discharge respond rapidly to atmospheric precipitation (Małecka *et al.* 2007). Most studies on spring discharge in the Flysch Carpathians in Poland indicate that groundwater discharge rarely exceeds 1 L s^{-1} and the vast majority of springs yield less than 0.1 L s^{-1} (Łajczak 1996; Buczyński *et al.* 2007; Rzonca *et al.* 2008; Mocior *et al.* 2015). Furthermore, the springs are characterized by strong variability in discharge over the course of the year. Some of these springs may even be called seasonal (Siwek *et al.* 2009; Moniewski 2015). However, several higher discharge springs were identified on the slopes of the Polonina Wetlinska Massif in the eastern part of the flysch-type Carpathians, called Outer Eastern Carpathians. Their mean discharge ranged from 1 to 9 L s^{-1} (Mostowik *et al.* 2016). The topographic catchments of these springs are small at 4 to 40 hectares. Most are characterized by permanent outflow regardless of meteorologic conditions. It is possible to conclude here that even in regions with low aquifer capacity, local conditions may lead to the emergence of relatively high discharge springs.

Spring recharge in flysch areas is associated with the presence of numerous low capacity aquifers (Chełmicki *et al.* 2011). In most cases, these small aquifers resemble

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one another in terms of spring discharge as well as physical and chemical properties of water. Yet, even in fairly small and lithologically homogeneous catchments, large differences in spring discharge, water temperature, and physical and chemical properties of spring water have been detected (Siwek *et al.* 2013).

The determination of the groundwater capacity recharging springs is possible with the use of a discharge recession curve for dry periods. This method is particularly useful in the study area, where highly invasive research (e.g., drilling) is not permitted in the interest of environmental protection in Bieszczadzki National Park. The recession curve is quite useful in the identification of regional hydrogeologic conditions. Applications of this method include identification of discharge characteristics and aquifer storage capacity (Korkmaz 1990; Dewandel *et al.* 2003; Malik & Vojtková 2012; Farlin & Maloszewski 2013; Bart & Hope 2014), analysis of drainage mechanisms (Malik & Vojtková 2012), and hydrograph separation (Eckhardt 2005). Thus far, recession curves have been used in most cases to help determine the hydraulic parameters of karst aquifers and the degree of karstification as well as the susceptibility of groundwater to pollution (Korkmaz 1990; Padilla *et al.* 1994; Malik 2007; Raeisi 2008; Chen *et al.* 2012; Malik & Vojtková 2012). The other way to approximate the capacity of aquifers along with groundwater residence time and circulation depth in selected areas can be done using environmental tracers (Zuber 1986; Zuber *et al.* 1986) or rates of change in water temperature (James *et al.* 2000; Szczucińska & Wasilewski 2013).

The state of spring research in the Polish Carpathians remains limited, which may be associated with the presence of a large number of low discharge springs. A review of the research literature indicates that the only high discharge springs in the Polish Carpathians are karst springs (Barczyk 2003), fissure and fissure-karst springs (Humnicki 2012a, 2012b), and fissure-bed springs (Łajczak 1981; Jokiel 1997). Given that flysch areas are generally believed to be poor in groundwater, it is important to identify key hydrogeologic conditions that sustain the few available relatively high discharge springs. Hence, the purpose of the paper is to assess the capacity of the flysch aquifer feeding springs in the Outer Eastern Carpathians on the example of the Polonina Wetlinska Massif. The paper will aim to answer the following questions: (1) What is the capacity of the studied aquifer? (2) What is the approximate water residence time for this aquifer? (3) What factors determine the occurrence of springs characterized by high discharge relative to what is expected in flysch areas?

STUDY AREA

Environmental and hydrogeologic settings

The Carpathian Flysch Belt consists of deep marine sedimentary rocks formed in foreland basins during the Alpine orogeny. The Polonina Wetlinska Massif, which is representative of the pristine environment of the Outer Eastern Carpathians in Poland, belongs to Silesian tectonic units. Two flysch complexes were identified in this area: (1) sandstone–shale member and (2) Otryt sandstone member (up to 2,000 m thick). The former consists of shale, laminated sandstone, and sandstone of medium and low thickness. The latter is formed of strongly cemented, thick and weathering resistant sandstone strata interbedded with minor shale layers (Haczewski *et al.* 2007). The pattern followed by the main ridge of Polonina Wetlinska is in agreement with the pattern followed by rock formations (ESE–WNW) that dip steeply (45° to 70°) towards the northeast or according to the gradient of the northern slope. Lateral ridges spur perpendicularly from the main ridge and are characterized by a step-type profile that reflects the resistance of rock beds to weathering – the more resistant rock beds are reflected by steep parts of slope and less resistant by gentle slope gradients. The study area is characterized by the irregular network of tectonic discontinuities (faults and fissures), which may affect the groundwater circulation patterns.

Water-bearing horizons found across Polonina Wetlinska are the Otryt sandstone, which serves as a fissure- and pore-type medium. The flow of water occurs in most cases via extension fractures in sandstone, as its degree of porosity is merely 2% to 6% (Królikowski & Muszyński 1969). The low storage of groundwater is caused by limited water retention in the permeable zone, given its small thickness (less than 40 m). In addition, the hydraulic conductivity is also low, with a mean value of

1.4×10^{-6} m s^{-1} up to a depth of 20 m, and 2.4×10^{-7} m s^{-1} in the range from 20 to 40 m (Chowaniec *et al.* 1983). The low values of the hydraulic conductivity provided in the literature for the Otryt sandstone most likely do not factor in the presence of fissures associated with fault lines and other geologic features. The presence of such features may locally increase the permeability of bedrock. The study area does include fissure- and debris-type springs, including many overflow springs (Królikowski & Muszyński 1969; Rzonca *et al.* 2008). The groundwater component of river runoff in the catchments originating in Polonina Wetlinska ranges from 2.4 to 6.8 L s^{-1} km^{-2} (Plenzler *et al.* 2010).

The study area is located in the temperate climate zone. Atmospheric precipitation increases along with elevation from 1,200 mm to 1,700 mm per year (Laszczak *et al.* 2011). The highest precipitation amounts over the course of the year are recorded in summer months. The slopes of Polonina Wetlinska are covered with forest up to an elevation of about 1,150 m. Subalpine meadows and alpine meadows are found at higher elevations.

Characteristics of the studied springs

The studied springs are situated in the near-ridge area of the Polonina Wetlinska Massif at an elevation ranging from 995 m to 1,101 m, immediately below the upper timberline. The springs issue from packets of thick-bedded Otryt sandstone up to 200 m in thickness (Figure 1; Haczewski *et al.* 2007). The studied springs are classified as slope-type springs based on their geomorphologic location. Channel heads can be found above springs no. 3 and 7. Dry V-shaped valley sections can be found above springs no. 4 and 5. All of the studied springs are classified as rheocrene springs – either debris or fissure-debris-type (Mostowik *et al.* 2016). Mean discharge in the studied springs in the study period ranged from more than 3 to almost 10 L s^{-1} (Table 1). Minimum discharge was recorded in autumn (September to December), with springs no. 3 and 7 temporarily running dry. Maximum discharge occurred usually in May and was associated with periods of elevated cumulative rainfall as well as high groundwater levels in the period following snowmelt. The one exception was spring no. 4, where

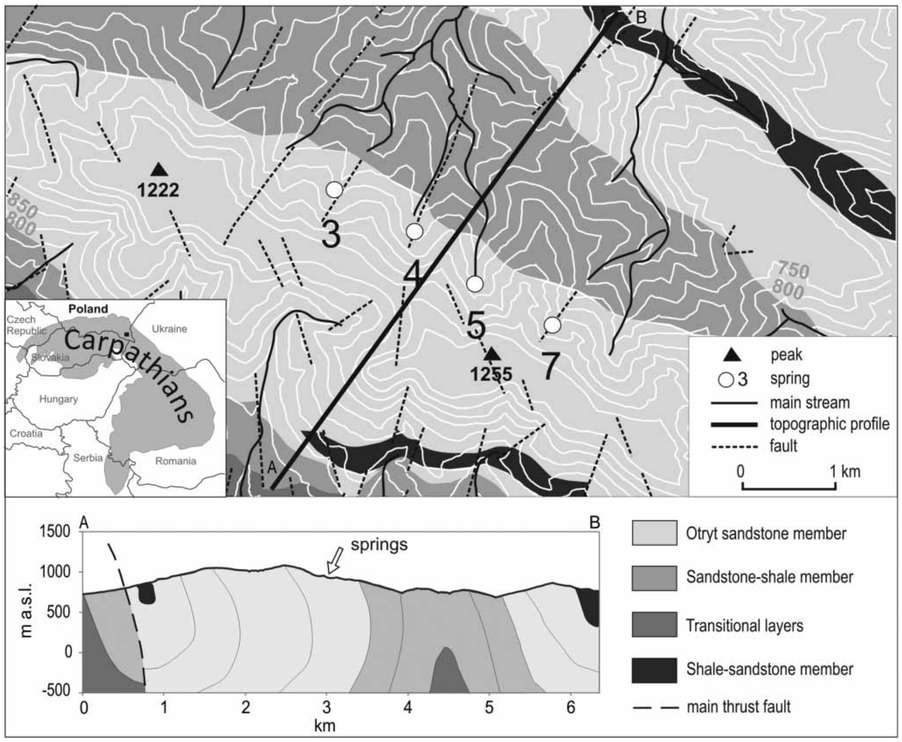

Figure 1 | Location of the studied springs and the geological setting (Mastella & Tokarski 1995).

Table 1 | Characteristics of the studied springs

Spring ID[a]	**3**	**4**	**5**	**7**
Research period	09.07.2013–27.11.2015	09.07.2013–27.11.2015	11.09.2012–27.11.2015	27.07.2012–16.11.2015
Q_{min} [L s^{-1}]	0.0	2.6	1.0	0.0
Q_{mean} [L s^{-1}]	6.2	6.7	9.5	3.2
Q_{max} [L s^{-1}]	21.0	38.4	31.4	28.1
I_v [–]	–	14.2	28.5	–
Spring discharge in hydrological years 01.11.2013–31.10.2015				
Q_{min} [L s^{-1}]	0.0	2.6	1.0	0.0
Q_{mean} [L s^{-1}]	6.1	6.9	11.2	3.1
Q_{max} [L s^{-1}]	21.0	21.8	31.4	28.1
Geomorphological features				
Contributing area [ha]	5.1	8.6	38.1	4.3
Elevation [m]	998	995	1,021	1,101
Morphology	Channel head	V-shaped valley	V-shaped valley	Channel head

[a] Spring ID after Mostowik *et al.* (2016).

maximum discharge occurred in November, and was also associated with high precipitation. Although the research periods are not completely the same for all studied springs they allow comparison of recession curves for various filling levels of the aquifer. Moreover, the discharge values for the studied period do not differ significantly from the discharge values for the common period of measurements for all springs (Table 1). Spring variability index values classify all the studied springs as variable ones.

METHODS

Water levels and water temperature were measured continuously for selected springs from 2012 to 2015 (springs no. 5 and 7) and from 2013 to 2015 (springs no. 3 and 4). The OTT Orpheus Mini water level loggers were used, characterized with an accuracy of ±1 mm. Data points were noted for hourly time intervals based on an average of measurements performed every 10 minutes. Spring discharge was measured volumetrically under various water levels in order to construct rating curves. The mean uncertainty of discharge measurements was 3.8%. Hydrographs were produced using daily data averaged on 24 daily measurements. Spring variability index (I_v) was then calculated for the studied springs in the form of the ratio of maximum (Q_{max}) to minimum discharge (Q_{min}) for the observation period (Netopil 1971):

$$I_v = \frac{Q_{max}}{Q_{min}}. \quad (1)$$

Daily precipitation obtained from the Institute of Meteorology and Water Management – National Research Institute meteorological station in Dwernik (518 m a.s.l.) for the period 2012–2015 was used in the analysis of meteorologic conditions.

Spring discharge measurement data can be used to estimate the supply of groundwater in selected aquifers (Boussinesq 1904; Maillet 1905). A recession curve is used in the estimation process. It shows the stage of groundwater depletion on a hydrograph. The curve is described by the exponential decline of discharge equation or the Boussinesq (1904) equation, which is commonly used in the analysis of spring recession curves (Maillet 1905; Castany 1962, 1968; Brutsaert & Nieber 1977; Korkmaz 1990; Padilla *et al.* 1994; Tallaksen 1995; Amit *et al.* 2002; Buczyński & Rzonca 2011):

$$Q_t = Q_0 \cdot e^{(-\alpha t)} \quad (2)$$

where Q_t is final discharge during the recession period (L s^{-1}), Q_0 is initial discharge during the recession period

($\mathrm{L\,s^{-1}}$), α is recession coefficient ($\mathrm{days^{-1}}$), and t is recession time (days).

In humid climates, recession might be influenced by frequent precipitation events, which results in large differences in the various segments of recession (Dewandel *et al.* 2003). In order to minimize the effects of these differences on the results, it is recommended that a standard length recession be used that differs for each given geographic region depending on natural factors (Tallaksen 1995). This is why hydrograph segments were selected for analysis characterized by a decline in discharge lasting no less than 7 days and not longer than 20 days. For the two markedly different recession periods that summed up to yield total duration time, recession coefficients (α) were calculated for the steeper segment and the less steep segment using the following equation:

$$\alpha = \frac{(\ln Q_0 - \ln Q_t)}{t}. \tag{3}$$

Coefficient α represents both the storage and the hydraulic properties of the aquifer. Based on recession curves, the master recession curves (MRCs) for each of the studied springs were created. Maillet's formula (2) describes the discharge characteristic of a linear reservoir and considers the discharge as the proportional to storage capacity as $Q = \alpha \times W$, where W is the storage capacity (Castany 1968; Korkmaz 1990). This parameter quantifies the amount of water (cubic meters) stored in the aquifer at the beginning of the dry period. Rearranging and allowing this formula for units gives:

$$W = \frac{(86400 \cdot Q_0)}{\alpha}. \tag{4}$$

The coefficient of recession can also be used to determine the residence time of water (T) in a water-bearing system (Boussinesq 1904; Farlin & Maloszewski 2013). This relationship is expressed by the following equation:

$$\alpha = T^{-1}. \tag{5}$$

Given the size of the analyzed sample, the determination of the relationship between residence time in a water-bearing system (T) and storage capacity (W) was made using the non-parametric rank correlation coefficient (Spearman 1904).

Approximated turnover time (days) (R) was determined based on the relationship between aquifer capacity (W) and mean annual spring discharge (Q_{mean}):

$$R = \frac{W}{(86400 \cdot Q_{mean})}, \tag{6}$$

which, in fact, is:

$$R = \frac{Q_0}{(\alpha \cdot Q_{mean}).} \tag{7}$$

In order to determine spring recharge mechanisms (fissure- or pore-type) and associated rates of recession, the authors decided to use a diagram of cumulative discharge frequencies – where frequency of occurrence is plotted on a probability scale and discharge on a logarithmic scale (Buczyński & Rzonca 2011). The shape of each plot and even each fragment may be interpreted in the context of spring recharge mechanisms as well as associated rates of drying. Straight segments on diagrams of discharge represent subpopulations following a distribution similar to a log normal distribution and may suggest that one recharge mechanism is clearly dominant in terms of the water-bearing horizon and pattern of drainage. However, this type of analysis does not yield unambiguous information indicating which pattern of spring recharge is the dominant one. On the other hand, changes in the diagram's slope suggest a multi-modal population distribution and changes in the predominant recharge mechanism (e.g., during strong drought).

RESULTS

Hydrometeorologic conditions

The period 2012–2015 was characterized by fairly low annual precipitation compared to the period 1986–2015 with mean annual precipitation at 1,005 mm. Annual precipitation for the study area for selected hydrologic years was 936 mm in 2013, 1,034 mm in 2014, and 560 mm in

2015. The dry period makes it possible to calculate the springs' recession coefficients and storage capacity (Dewandel *et al.* 2003; Raeisi 2008). The largest precipitation was noted for May, June, and July, while the lowest was noted for the period November–February. The exception was November 2013 with a precipitation of 112.68 mm. Autumn seasons in the study period were characterized by an occurrence of long-lasting and exceptionally strong drought, one of the most extreme in the last 50 years. Most of the analyzed spring recession curves were generated for the period April–July (39%), while 30% of the curves were generated for November, December, and January.

Spring water temperature

The mean temperatures of water in the studied springs ranged from 5.4 °C (no. 5) to 6.0 °C (no. 4), which are typical values for springs found at lower elevations at this geographic latitude. One particularly crucial detail is the small change in water temperature over the course of the year. For example, in spring no. 5, the annual temperature range did not exceed 0.2 °C (Figure 2). In addition, no seasonal cycles in water temperature were observed. No temperature changes were observed following precipitation events and snowmelt events when spring no. 5 yields greater discharge (Figure 3). Other springs were found to experience seasonal changes in water temperature, but the range usually did not exceed 2 °C. Large changes in temperature were not observed during periods of increasing discharge (Figure 3). However, water temperatures usually did decline 0.2 to 0.5 °C after 10 to 20 days following snowmelt events and heavy autumn rainfall. The highest variation in water temperature (up to 4 °C) was observed only in the case of spring no. 3 (Figure 2). A large increase in water temperature was observed during a major drought, when measured water temperatures exceeded 12 °C for a short period. However, high temperatures occurred only immediately following the cessation of discharge, when the recorded temperature represents spring water and surfaces in the channel head. The study does not focus on temperatures measured in the

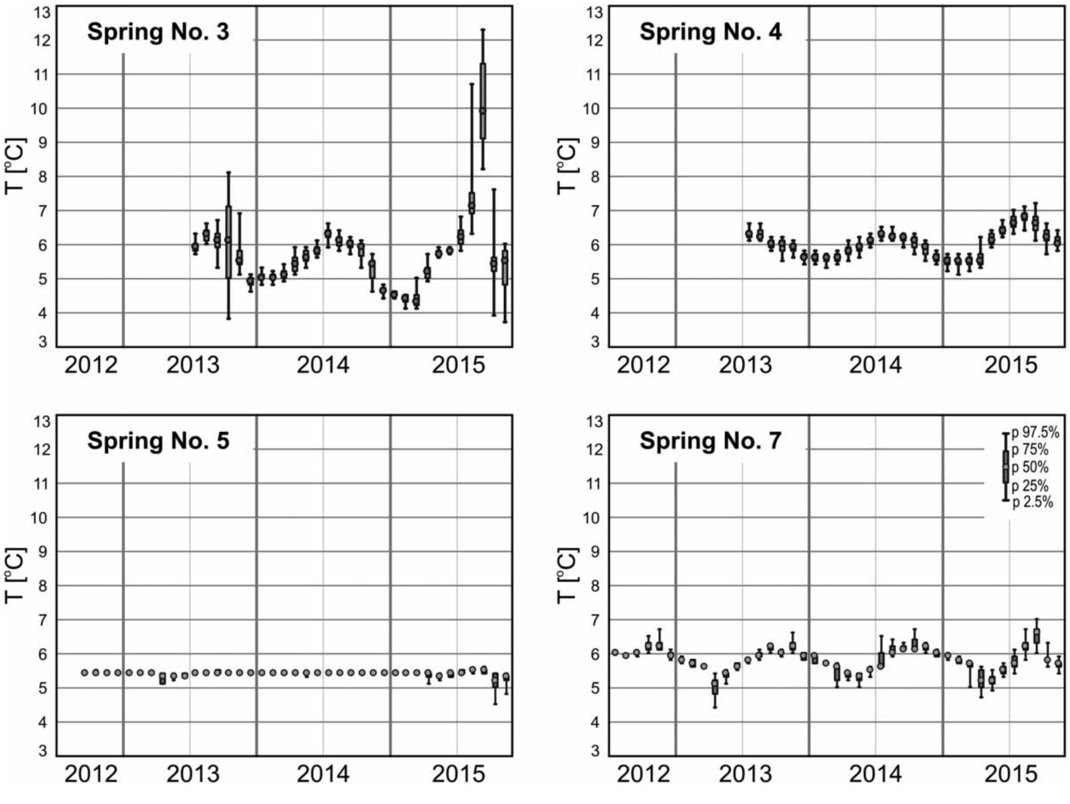

Figure 2 | The monthly percentiles of spring water temperature in 2012–2015.

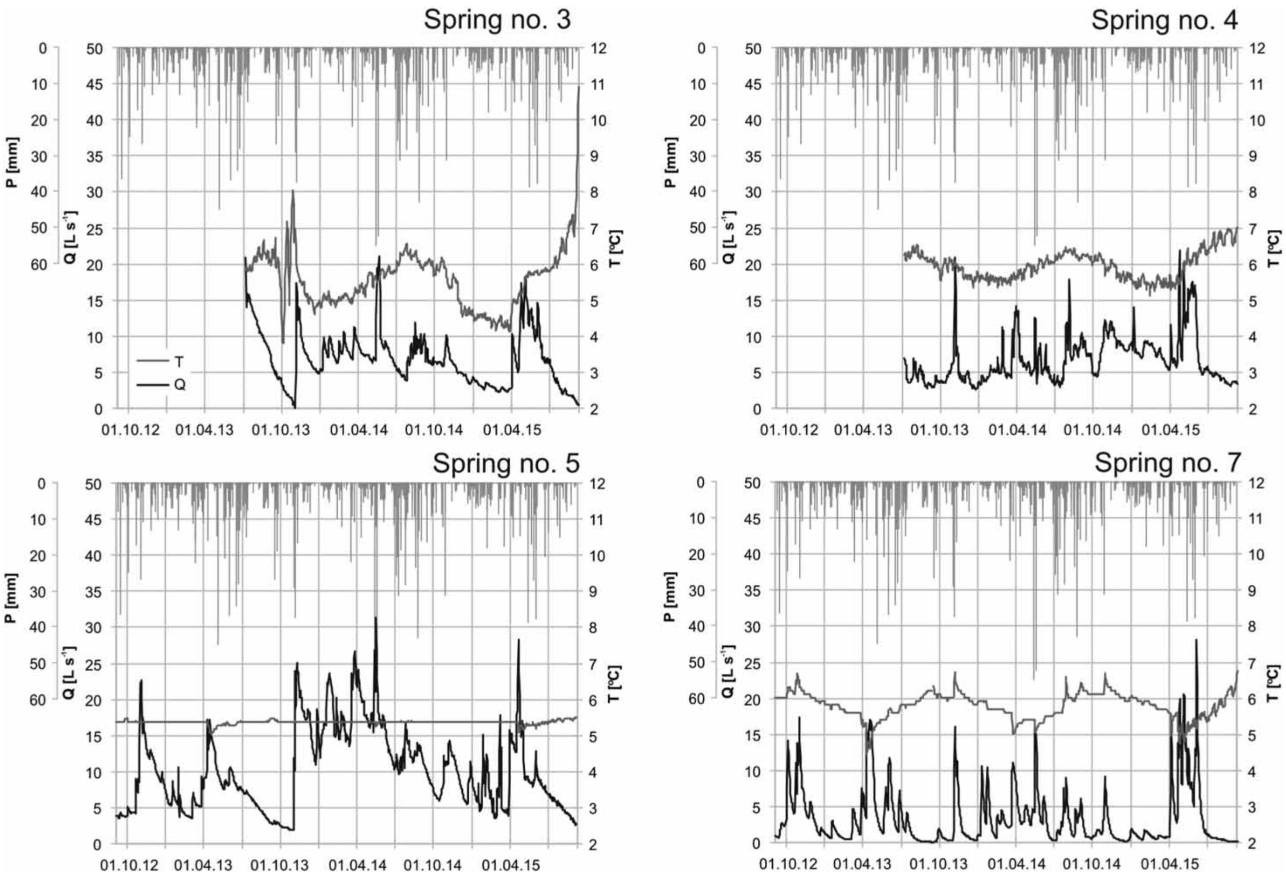

Figure 3 | The spring discharge (Q), water temperature (T), and daily precipitation (P) in 2012–2015.

absence of spring discharge. Shortly following the resumption of discharge, spring water temperature did return to a more typical 5 to 7 °C.

Characteristics of recession

MRCs for four springs were created based on a total of 69 recession curves produced in the period 2012–2015 (Figure 4). Three of the MRCs are characterized by a two-stage groundwater depletion process, as indicated by differences in the exponential decay of the curves described by the coefficient of recession (α). Higher α coefficients are noted for the initial influenced sections of the recession curve, which indicates quick-flow (quick component). Smaller α coefficients are noted for later stages of recession, which indicates slow component (uninfluenced stage). In the case of spring no. 5, the MRC is characterized by one small coefficient of recession.

The determined recession parameters for the four studied springs are presented in Table 2. The coefficient of recession for the analyzed sections of recession curves ranged from 0.012 to 0.229 d^{-1}. The typical value range of the coefficient, defined as the span between the 10th and 90th percentiles, ranged from 0.017 to 0.142 d^{-1}. Springs no. 3 and 5 were characterized by similar and relatively low values of the coefficient of recession (approximately 0.02 d^{-1}). As a result, the calculated storage capacity recharging springs in the studied area were also substantially differentiated. The estimated storage capacity for springs no. 3 and 5 ranged from 16.3×10^3 to 111.3×10^3 m^3. The range for springs no. 4 and 7 was only 1.2×10^3 to 34.4×10^3 m^3. The smallest storage capacity by far for an aquifer was calculated for spring no. 7. The calculated storage capacity divided by the topographic catchment areas is equivalent to a water column of 114 to 555 mm.

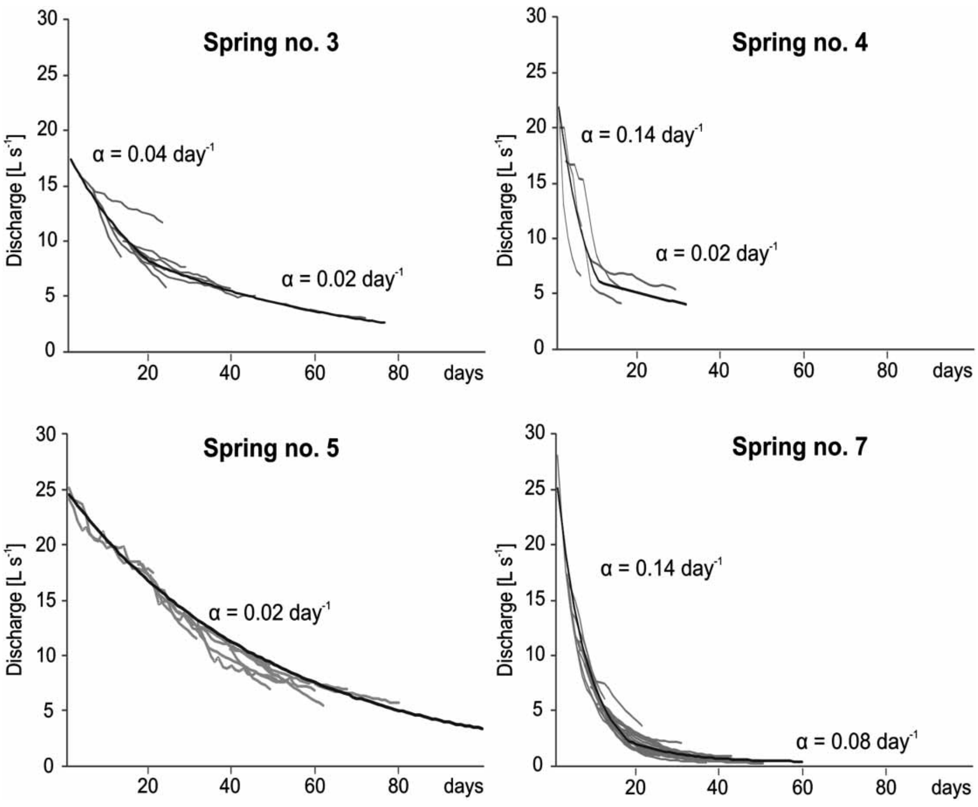

Figure 4 | Master recession curves of the studied springs.

Table 2 | Recession parameters of the studied springs

Spring no.		**3**	**4**	**5**	**7**
N		11	6	18	34
α [d^{-1}]	p10	0.015	0.021	0.013	0.045
	p50	0.022	0.089	0.020	0.078
	p90	0.058	0.207	0.046	0.157
	C$_d$	0.46	0.64	0.31	0.34
W [$10^3 \times m^3$]	p10	16.2	4.5	20.5	1.2
	p50	28.3	15.2	49.0	4.9
	p90	45.0	34.4	111.3	11.0
	C$_d$	0.33	0.22	0.17	0.33
T [d]	p10	17.3	4.8	21.8	6.4
	p50	46.5	11.3	50.1	12.8
	p90	65.4	47.6	75.1	22.5
R [d]	p10	30.2	16.2	24.9	4.5
	p50	52.8	55.4	59.3	17.8
	p90	84.0	125.0	134.9	39.9

C$_d$, coefficient of quartile dispersion.

It is noteworthy that the largest distribution of values for the coefficient of recession was noted for spring no. 4 (Figure 5). This particular spring both increased its discharge in precipitation periods and maintained relatively high discharge in dry periods. On the other hand, differences in the value of the coefficient of recession were smallest for springs no. 3 and 5. Coefficients of recession indicate that the average residence time of water recharging springs no. 3 and 5 is about 50 days, with a maximum of 82 days. A much shorter residence time was noted for water recharging springs no. 4 and 7, where the average duration was only about 12 days, with a peak value of 48 days. The annual average turnover time was calculated to be 50 to 60 days for springs no. 3 and 5. On the other hand, the shortest turnover time was found for spring no. 7 at about 18 days.

In three of the studied springs (no. 3, 4, 5), one additional correlation has been observed between storage capacity (W) and water residence time (T). The value of Spearman's rank correlation coefficient ($p \leq 0.05$) for these two parameters ranges from 0.58 to 0.83 (Figure 6).

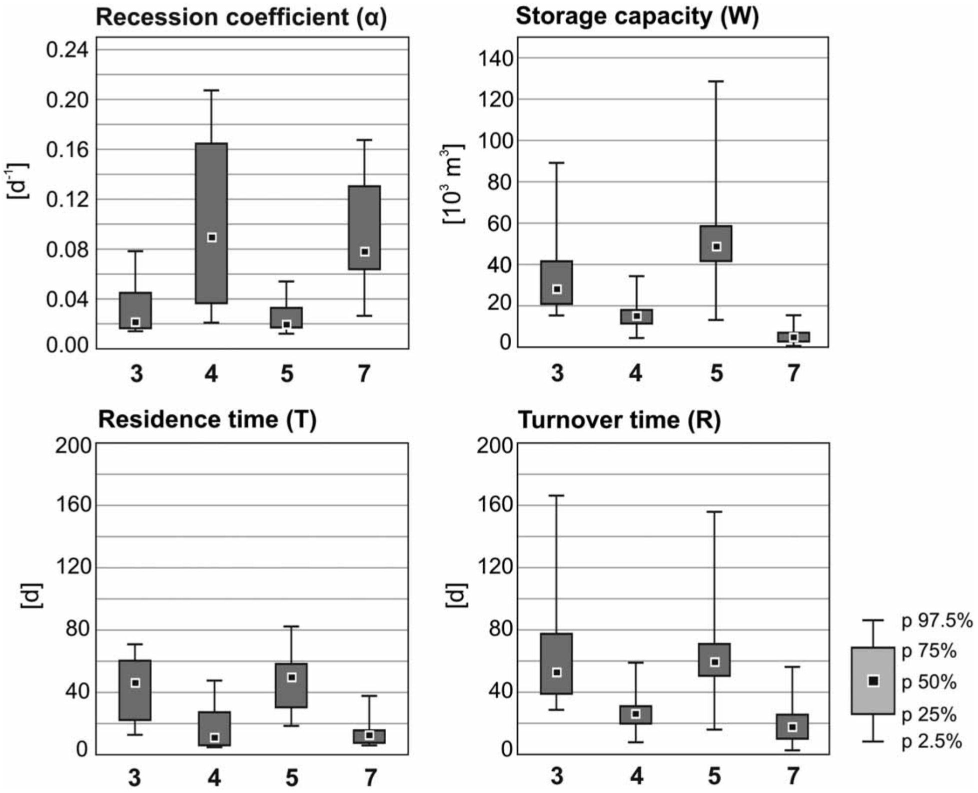

Figure 5 | Characteristic percentiles of recession parameters of the studied springs.

In the case of spring no. 7, the relationship between water residence time and storage capacity is quite different, as the correlation between these parameters is weak and its sign is negative ($r = -0.51$, $p \leq 0.05$).

The data provided above indicate that spring no. 7 differs from the other studied springs in terms of aquifer capacity, turnover time, and the relationship between water residence time and storage capacity. However, of the studied springs, spring no. 7 has the smallest recharge area and smallest mean annual discharge. In addition, it can also run dry from time to time.

Diagrams of cumulative discharge frequencies representing springs no. 4 and 5 (Figure 7) feature very steep slopes, which are a sign of a small range of discharge values. The lowest discharge for these springs is more than 1 L s^{-1} (no. 5) and 2 L s^{-1} (no. 4). Their discharge changes by one order of magnitude. The diagrams produced for these springs do not show any strongly heterogeneous distributions (e.g., changes in slope) that would suggest a multimodal population distribution. The discharge diagram for spring no. 7 also features a straight line. In this case, heterogeneous sections appear only in the period preceding cessation of discharge (below 0.2 L s^{-1}). The variances in discharge, as represented by the slope in the diagram, are fundamentally different from those noted for springs no. 4 and 5. In the case of spring no. 3, one can note strong heterogeneity in the cumulative discharge frequency diagram (Figure 7). The sharpest inflection point corresponds to a discharge equal to 1.8 L s^{-1} (probability: 14%). This inflection point divides the diagram into two distinct sections. The first section (below 1.8 L s^{-1}) represents the recession mechanism for the spring during strong drought periods detected during the study period. The second section includes one more inflection point – a much less distinct inflection point – that corresponds to a discharge equal to 6.2 L s^{-1} (probability: 49%). It is difficult to discern the extent to which the recharge mechanism changes at this less visible inflection point. The section from discharge equal to 1.8 to 6.2 L s^{-1} represents a spring recharge mechanism associated with medium water storage stages. On the

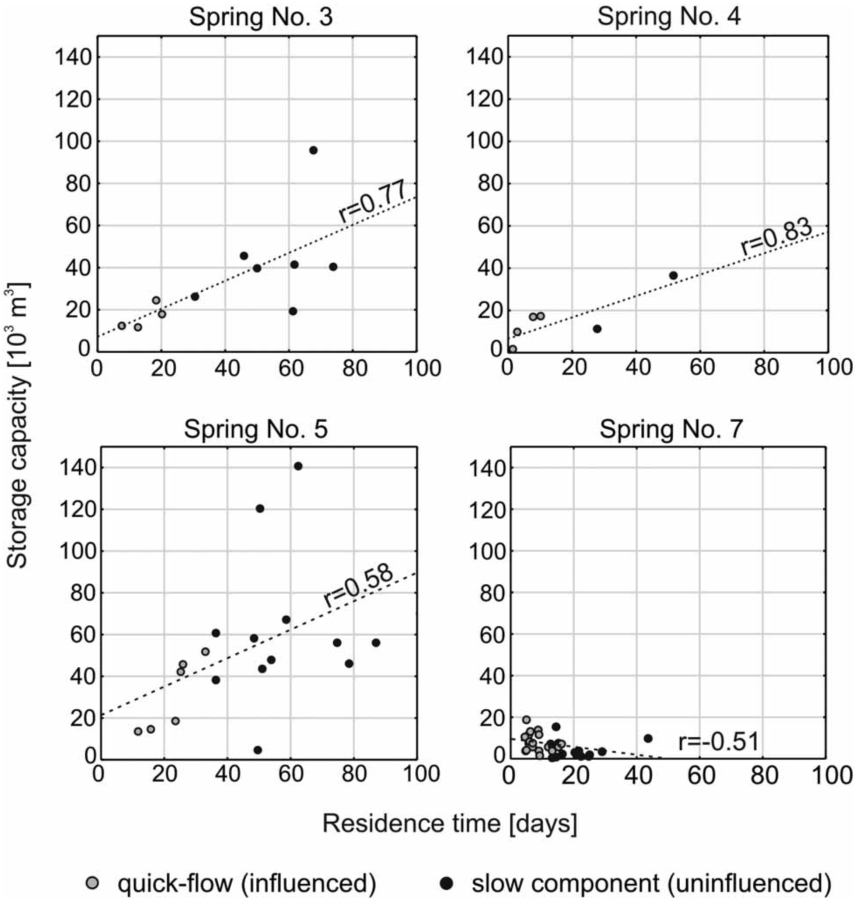

Figure 6 | The residence time of water in the aquifer versus the storage capacity of the studied springs.

other hand, the section above discharge equal to 6.2 L s^{-1} represents fairly high and high discharge occurring immediately following precipitation and snowmelt events.

DISCUSSION

Existing studies on flysch mountain areas indicate that sandstone is most often a water-bearing rock, while fractured marl and shale rocks are rather aquitards. The water-bearing capacity of sandstone is mostly a product of its high number of fissures. On the other hand, pore water is mostly detected in thick weathering cover (Jokiel 1997; Łajczak 1981; Chełmicki *et al.* 2011). There is a fairly straightforward system of spring recharge – slopes are dominated by fissure-type springs, while valley floors are dominated by pore-type springs. The presence of small local aquifers results in numerous springs that yield little water (Chełmicki *et al.* 2011). This is why the study area is unique in that it features high discharge springs (>3 L s^{-1}), which are recharged by fractured Otryt sandstone layers with numerous fissures. As a result of this, the Otryt sandstone aquifer is characterized by different recharge mechanisms.

A log-normal distribution of the recorded discharge values for springs no. 4 and 5 (Figure 7) may suggest that a single recharge mechanism is clearly dominant in both springs in terms of the water-bearing horizon and pattern of drainage (i.e., fissure- or pore-type aquifer). Differences in discharge in the two springs result from groundwater depletion patterns (Figure 4), but with no changes in the predominant recharge mechanism (e.g., during strong drought). In addition, springs no. 4 and 5 feature the highest mean and maximum discharge values among the studied springs as well as strongest discharge continuity. Hence, it may be

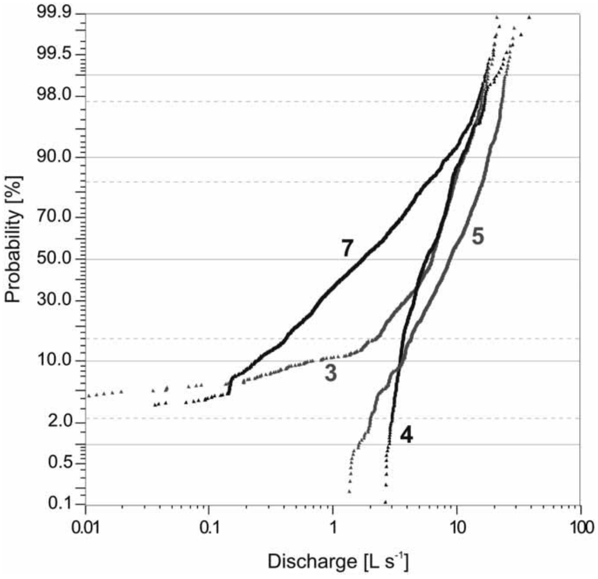

Figure 7 | Diagram of relative frequencies of discharge rates for the studied springs.

concluded that subsystems of the aquifer recharging these two springs are significantly more capacious compared with those recharging other springs in the present study, while the predominant recharge pattern is based on fissure-originating water influx. The discharge diagram for spring no. 7 also features a straight line but the slope in the diagram is fundamentally different from those noted for springs no. 4 and 5. In addition, spring no. 7 features the lowest storage capacity and the shortest turnover time of all the studied springs. It is a spring with the lowest mean discharge and intermittent flow which indicates that this spring is recharged by a low capacity pore-and-fissure-type subsystem of the groundwater aquifer. In the case of spring no. 3, strong heterogeneity in the cumulative discharge frequency diagram indicates the changing of the predominant recharge mechanism (Buczyński & Rzonca 2011). Spring no. 3 is characterized by high storage capacity as well as long turnover time compared with the other studied springs. In addition, this spring functions intermittently and features the largest variances in water temperature (Figure 2), which further indicates the presence of a complex subsystem of the aquifer characterized by fissure-and-pore-type recharge mechanisms.

Generally, the presence of statistically significant relationships between water residence times (T) and storage capacity (W) indicates a homogeneous recharge system (Humnicki 2012a, 2012b), and the groundwater supply is not directly affected by short-lasting precipitation and snowmelt events. This is not necessarily the case in the study area where the multiple spring recharge systems occur. Despite the significant relationship between the two recession parameters in spring no. 3, it is important to consider its key characteristics such as intermittent flow and its largest fluctuations in water temperature relative to the other studied springs. These features tend to contradict the possibility of the occurrence of a homogeneous spring recharge system. However, in the case of spring no. 7, the highest detected storage capacity corresponds to the shortest water residence time. This indicates a complex recharge system, in which shallow infiltration water is the predominant type. This water rapidly reaches the spring via fissures following precipitation and snowmelt events. In addition, the pore system does not strongly retain this water.

The presence of many different types of recharge mechanisms across such a small region may be due to tectonics in the Outer Eastern Carpathians. A dense network of faults and associated fractures and fissures in rocks all affect the occurrence of numerous groundwater outflows in the study area (Mocior *et al.* 2015). It is fissures that play a significant role in groundwater flux in the sandstone here (Kowalski 1980; Kleczkowski 1991; Chowaniec 2009). Most of these springs are low discharge, but a number of high discharge springs have also been noted in the area. These are most likely associated with high flow areas near fault lines (Mocior *et al.* 2015; Mostowik *et al.* 2016). In the Flysch Carpathians, faults determine the supply of groundwater available to springs (Chełmicki *et al.* 2011). Faults can produce a flow-through recharge mechanism that favors the occurrence of high discharge springs. On the other hand, faults may form a barrier that leads to forming an aquifer with a high total volume, which is located mostly below the drainage system. Probably, springs no. 3 and 7 are such overflow springs related to fault zones, that allow for recharge in the more distance areas, exceeding the topographic catchments of the springs. This would explain the rapid reaction of spring discharge to recharge and the stability of spring water temperature at the same time.

The variability of spring water temperature reflects water circulation conditions and indirectly provides information on aquifer static volume. Minor changes in spring

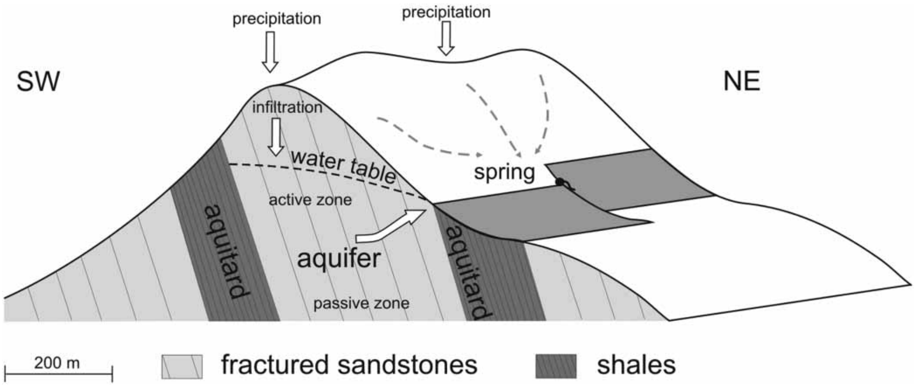

Figure 8 | Schematic outline presenting the overflow system of springs on the Polonina Wetlinska.

water temperature indicate capacious aquifers recharging springs that experience averaged temperatures over longer periods of time (Kisiel *et al.* 2015). The presence of an overflow mechanism favors high discharge, which may decline rapidly once the active zone of the aquifer is depleted (Witczak *et al.* 2002; Rzonca *et al.* 2008). Thus, the calculated water residence time in a water-bearing system or average turnover time for an aquifer may be quite short as they reflect only the dynamic part of the aquifer (Figure 8). It is reasonable to presume that this recharge mechanism is utilized by springs that, on the one hand, are characterized by high discharge at a given time and a stable temperature throughout the year and, on the other hand, by low capacity and large fluctuations in discharge.

CONCLUSIONS

Four springs with atypically high discharge for a flysch-type aquifer were studied on the slopes of the Polonina Wetlinska Massif in the Outer Eastern Carpathians in Poland. The springs are fed by the Otryt sandstone aquifer. In the interest of environmental protection, the study was done by non-invasive techniques, namely, observing the rate and temperature of spring flow. Recession analysis was applied to the flow for dry periods to provide answers to the questions: (1) What is the capacity of the studied aquifer? (2) What is the approximate water residence time for this aquifer? (3) What factors determine the occurrence of springs characterized by high discharge relative to what is expected in flysch areas?

1. The mean storage capacity of the groundwater subsystems recharging the examined springs ranges from 4.9×10^3 to 49×10^3 m^3. This is much higher than can reasonably be expected considering the surface area of their topographic catchments and indicates that at least some springs must be experiencing groundwater influx from outside their catchments.
2. The approximate water residence time for the studied aquifer ranges from 11.3 to 50.1 days and together with other recession parameters indicates the occurrence of the multiple spring recharge systems even in a small area. Three types of spring recharge mechanisms were identified in the study area: (i) simple fissure type, (ii) complex fissure-pore type, (iii) complex pore-fissure type. Springs producing the highest discharge are recharged first and foremost by the largest fissure-type aquifers.
3. Local tectonic effects play a crucial role in the studied aquifer. The presence of networks of fissures and rock fractures in the near vicinity of fault zones enables the accumulation of water and the occurrence of overflow springs with high discharge by flysch standards.

While the springs in the study area are characterized by dynamically changing discharge, they exhibit a fairly stable temperature throughout the year. The fissure systems facilitate rapid recharge of the aquifer by precipitation and melting snow, leading to a rapid response of spring discharge. At the same time, the static volume of aquifer is large enough to stabilize the water temperature.

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