Temporal variability of springs in catchment areas located in the Sudeten Mountains

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ABSTRACT

This paper describes the results of research into the freshwater springs occurring in the crystalline and compact sedimentary rocks in the Sudeten Mountains. The research consisted of three series of measurements taken in the hydrological year 2013 in four test catchments (Machowski Stream, Inflow at the foot of Mount Grodziec, Podgórna, Mostowy Stream). Data analysis indicated that the number of springs, spring discharge and physicochemical properties of the water were subject to significant temporal variation. The temporal variability of the spring density index ranged from 7 to 31%. Temporal variations in the total yield of the springs fluctuated between 34 and 63% and the minimum discharge variability index exceeded 100%. The study indicated that water flow in areas consisting of compact sedimentary rocks such as sandstone and marl is much more diffuse than in areas that are comprised primarily of crystalline rocks, which accounts for a lower yield and a decrease in temporal spring discharge variability. In areas made up of crystalline rocks, the higher yield and the higher spring discharge variability index point to cracks and fissures as the main recharge component, a feature characteristic of aquifers with high conductivity and low storage capacities.

Key words | compact sedimentary rocks, crystalline rocks, springs, Sudetes, variability index

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INTRODUCTION

A spring is a place where, without the agency of man, water flows from a rock or soil onto the land or into a body of surface water. Spring water provides a unique opportunity to study a range of subsurface processes (groundwater flow and active geologic processes) in regions without boreholes or wells. By using discharge measurements and physicochemical parameters of spring water, it is possible to determine the mean-residence time of the water, to infer the spatial pattern and extent of groundwater flow, to estimate basin-scale hydraulic properties or to calculate the regional heat flow (Manga 2001). However, studies indicate a high seasonal and spatial variability in the distribution, yield and physicochemical parameters of springs (Earman *et al.* 2008; Buczyński *et al.* 2011; Chełmicki *et al.* 2011). The spring density index and the physicochemical parameters of spring water are affected by stable factors such as the morphology of the terrain, its geological structure, the storage capacity and dimensions of the aquifer and the permeability of the rocks, as well as other changeable variables such as the amount and time of precipitation, air temperature and land management. The spring density index exhibits a strong positive correlation with the tectonic activity of the area, understood as the length of thrusts and faults per unit (Pacheco & Alencoão 2002; Corsini *et al.* 2009; Ozdemir 2011; Bense *et al.* 2013). The spring density index also increases at the place of contact between the two layers (permeable and non-permeable rock). The identification of areas with a high probability of the occurrence of springs is aided by characteristics such as elevation, slope, and the stream power index. The slope interval that most strongly favours the occurrence of springs is 15–25° (Corsini *et al.* 2009; Ozdemir 2011).

doi: 10.2166/nh.2017.229

Because the spring density index and natural characteristics of springs are an intermediate effect of the groundwater circulation pattern in the region, they can serve as proof of water resources and groundwater circulation patterns in a given geographic area (Mocior *et al.* 2015). Temporal variations of springs needs to be observed and documented on an ongoing basis in order to provide a credible basis for analysis. A detailed understanding of spring variations may facilitate the prediction of seasonal variability in the distribution, yield and physicochemical parameters of springs in other regions of the world that have a similar geological structure.

In Poland, the spring density index is highest in flysch formations (sequences of sedimentary rocks that consist of a sequence of shales rhythmically interbedded with thin, hard, graywacke-like sandstones) where figures as high as 50 springs per square kilometre have been recorded. The lowest spring density index (0.01) was recorded in the Polish Lowland (Waksmundzki 1972; Ciężkowski *et al.* 2001; Mocior *et al.* 2015). In the Eastern Sudetes the figures range from 1.3 to 25 (Buczyński *et al.* 2011) and up to as many as 60 springs per square kilometre (Bartnik & Walisch 1997), depending on the catchment under study.

Analyses of the outcomes of research conducted in the same areas at different times produce high variable results. Periodic studies and observations of changes in the discharge and physicochemical parameters of the springs indicate variability over the course of years, months and even days (Michalczyk 1997; Drużkowski 2000; Żelazny *et al.* 2013; Mocior et. al. 2015). In the Morawka catchment (the Eastern Sudetes), the spring density index ranged from 5.6 to 25.8 (Buczyński *et al.* 2011), depending on the time of mapping. In the Bystrzyca Dusznicka catchment figures ranging from 2.7 to 7.1 springs per km^2 were recorded (Buczyński & Rzonca 2011). The smallest spring in the Bystrzyca Dusznicka catchment had a discharge of 0.03–1.3 l s^{-1}, while the discharge of the largest spring in this catchment fell between 18 and 99.5 l s^{-1}. The amplitude of pH, electrolytic conductivity (EC) and temperature fluctuations at the same sites over the course of years were recorded respectively at 0.1–2.8 (with an average pH of 6.6), 5–127 μS/cm (with an average EC of 155.7 μS/cm) and 0.2–4.4°C (with an average water temperature of 6.3°C).

These studies prove that one-off mapping provides only a general idea of a given area's hydrogeology, which may change considerably depending on the season. Data analysis has to allow for the fact that the results obtained through one time hydrogeological mapping may differ significantly from those obtained through seasonal research or stationary measurements. The significance of this should not be underestimated, because the interpretation of the results of the study of springs is one of the factors included in the descriptive part of detailed hydrological and hydrogeological maps, as well as documents pertaining to the quality and quantity of groundwater resources. In some areas, especially mountainous regions where no groundwater wells are available, the only way to determine the hydrogeological and physicochemical parameters of the aquifer is through the study of local springs. Unfortunately, long-term, seasonal or stationary research, which could provide the data necessary to fully characterise the water regime, is often not feasible owing to financial or scheduling problems.

The aim of this paper is to analyse the variations in the number of springs, total spring yield, physicochemical properties of springs and comparison of springs in different geologies. A verifiable hypothesis assumes that the springs occurring in steep catchments will be characterised by a greater springs density index and, at the same time, greater variation in the number of springs and a greater variability ratio in the physicochemical parameters of the spring water. The hypothesis also assumes that the springs with drainage of crystalline rock will have higher but more varied discharge than outflows with drainage of compact sedimentary rocks. Research was conducted in the hydrogeological year 2013 in catchments characterised by similar meteorological conditions and land management strategies, but differing from each other in their geology and terrain morphology. Four research sites (catchments) were selected, with similar surface areas and located close to one another. Two of the catchments, differing from each other in terrain morphology, were made up mostly of compact sedimentary rocks, while the remaining two comprised primarily crystalline rocks. The catchments under study did not show signs of human activity intense enough to affect the discharge regime and physicochemical parameters of the spring water. Hydrogeological mapping formed the basis for the assessment of the number, distribution, discharge and physicochemical properties of the springs. Such mapping was carried out three times in each of the catchments, along with analyses of the variability of the spring density index, spring discharge, pH, conductivity and temperature.

STUDY AREA

The study area is located in south-western Poland and includes four catchments (Figure 1) that were selected to reflect the morphological and lithological diversity of the Sudetes. Two of them lie in a region of sandstone basement (catchment 1, Machowski Stream, and 2, Inflow at the foot of Mount Grodziec – Gierwielaniec & Radwański 1955; Cymerman 1991) and the other two are situated in an area of crystalline rocks (catchment 3, Podgórna, and 4, Mostowy Stream – Grocholski 1956; Cymerman 1989). They have been classified according to terrain inclination as steep and relatively gentle. Classification was made by calculating river valley inclination, which is the quotient of height differences and catchment length. Height differences range from 111 to 374 m (Table 1), while the river valley inclination varies from 0.03–0.08 m/m for gentle catchments to 0.16 m/m in the case of steep catchments. The areas of the catchments fall between 3.3 and 4.5 km^2.

The study area has a typically submontane climate that is influenced by air masses advancing from the Atlantic Ocean, Scandinavia, north-eastern Europe and occasionally from the Azores, northern Africa and southern Europe. The winds in the region are predominantly westerly and southwesterly. The average annual air temperature ranges from 4 to 6°C, depending on elevation. July is the warmest month of the year with an average temperature of 15.7°C, while January is the coldest, with an average temperature of only -3.2°C. The average annual precipitation is about 900–1,300 mm, reaching maximum values in July. The area is covered with snow for an average of 80–100 days a year. Low temperatures and high precipitation mean that the water balance for the local climate type – understood as the difference between precipitation and evaporation – is positive and reaches about 200–300 mm. The spatial distribution of precipitation is characterised by a progressive increase in the monthly and annual amount along with elevation, although it is also largely affected by the morphology of the terrain and slope exposure. The progressive increase in precipitation along with a 100 metre increase in elevation is from 65 mm to 86 mm (Pawlak 1997; Staśko & Tarka 2002).

The catchment areas of Machowski Stream (1) and Inflow at the foot of Mount Grodziec (2) are made up primarily of upper Cretaceous sedimentary rocks. Siliceous or loamy marls and fine-grained jointed sandstones cover most of the area, with mica schists, mylonites and dolomite rocks occurring only in the upper region of catchment 2 (Gierwielaniec & Radwański 1955; Cymerman 1991).

The other two catchments, Podgórna (3) and Mostowy Stream (4), are made up mostly of crystalline rocks. Their geological composition includes Precambrian orthogneisses, Proterozoic-Paleozoic mica schists and dolomite rocks. The only area composed of siliceous and loamy marls, and jointed sandstones is located in the eastern part of the Podgórna catchment and forms the watershed between the Podgórna and Bystrzyca Dusznicka rivers. In all of the catchments, alluvial deposits and thin diluvial clays occurs only within the river valleys (Grocholski 1956; Cymerman 1989).

In the Sudetes, the dominant aquifer type in Cretaceous formations is sandstone, which forms three or sometimes four water-bearing zones. These zones are usually found at depths of several to several hundred meters. Recharge of the upper water-bearing strata occurs directly through precipitation, while in the lower layers the process usually takes place around rock outcrops or areas of inflow of water from the Cretaceous formation's crystalline substratum (Tarka 2006).

Aquifers in crystalline areas of the Sudetes comprise between two and four water-bearing zones. In 2002, Stasko suggested that the vertical profile of crystalline rocks in the Sudetes be divided into three water-bearing zones with different filtration properties and reaction times of the groundwater table to precipitation. The uppermost zone, recharged by precipitation and meltwater and identified as the near-surface weathered-rock deposits, is characterised by a variable thickness (from 1 to 10 m), gravitational drainage capacity $\mu = 0.18$ and a permeability coefficient $k = 0.1$ m/d. The second layer is approximately 10–50 m thick

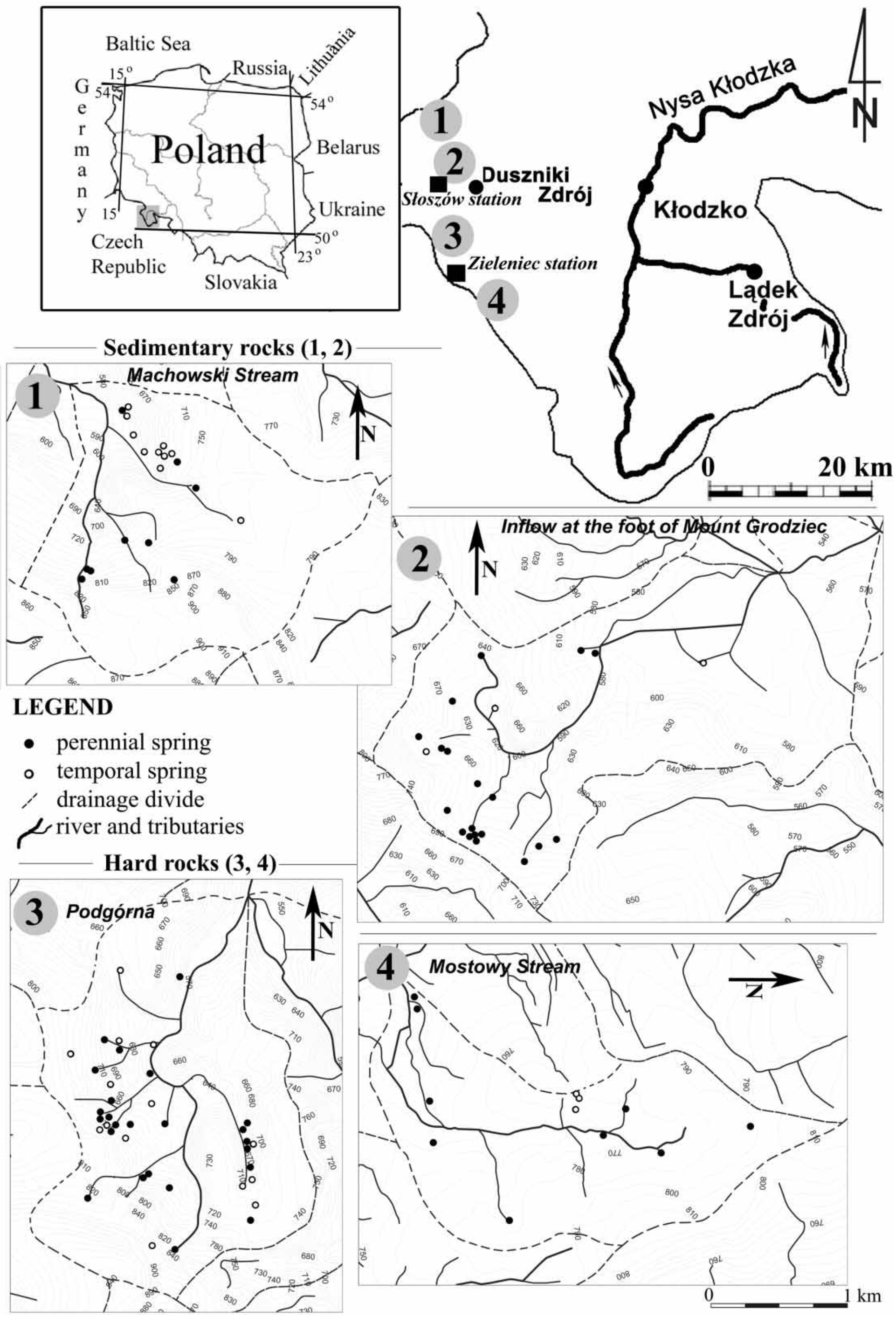

Figure 1 | Location of perennial and temporal springs in the four test catchments.

and composed of densely fractured rocks whose parameters differ from those of the uppermost stratum ($\mu = 0.008–0.05$, $k = 1$ m/d). The third layer consists of deep faults which form regional groundwater circulation routes. Rocks in this stratum have the lowest permeability and water storage capacities.

Table 1 | Characteristics of the catchment

Catchment no.	Catchment	Area (km^2)^a	River length (km)^a	Height differences – Min/Max^a (m)	River valley inclination (m/m)^b	Geology^c	Rocks^c
1	Machowski Stream	3.3	4.7	374–919/545	0.16	Compact sedimentary rocks	Sandstones, silica marls
2	Inflow at the foot of Mount Grodziec	4.5	3.8	254–802/548	0.08		Sandstones, silica marls
3	Podgórna	3.5	3.1	374–942/568	0.16	Crystalline rocks/ hard rocks	Mica schists, qurzites, sandstones, clay-silica marls
4	Mostowy Stream	3.6	3.6	112–817/705	0.03		Gneiss

[a] Topographic map data at 1:10,000 scale.

[b] Quotient of height differences and catchment length.

[c] Maps used (Gierwielaniec & Radwański 1955; Grocholski 1956; Cymerman 1989; Cymerman 1991).

METHODS

Catchment characteristic

Detailed hydrogeological mapping, when the whole catchment area was mapped on foot each time, was carried out three times in each of the catchments on the following days: 15–16 November 2012; 1–2 July 2013 and 29–30 October 2013. The research was conducted in accordance with the methodology, at times of low rainfall and when there was a low level of groundwater. Similar low water levels recorded in three measurement series (confirmed observations on flow of rivers and groundwater level in wells from the monitoring network of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) and Polish Hydrogeological Survey) should result in the smallest discrepancies in the number of mapped springs and translate into very minor variations in the discharge regime and physicochemical properties of the springs.

The Standardised Precipitation Index (SPI) was used to analyse rainfall levels in the years 1996–2013 at stations located within the catchment (Słoszów station/16.3729; 50.4189/located within catchment 2) or in its immediate vicinity (Zieleniec station/16.3871; 50.3334/located between catchments 3 and 4 and about 1 km away from them). The SPI index is used in the USA and in Europe, where it has become a standard tool to identify periods of drought and to estimate their intensity (McKee *et al.* 1995). The main virtue of this approach is that it facilitates the evaluation of rainfall conditions in various climates, regardless of the time scale. The SPI of any region is determined after analysing long series of precipitation over a certain period of time. The system of classifying rainfall conditions in Poland using the SPI, suggested by Łabędzki (2006) is presented in Table 2.

The calculation of the SPI for rainfall of a given volume (P), after normalising the precipitation series with the application of modulating function ƒ (P), can be done with the help of this formula:

$$SPI = \frac{f(P) - \bar{x}}{d}$$

where:

$f(P) = \sqrt[3]{P}$ is the normalised total annual rainfall,
$\bar{x}$ stands for the mean value of the normalised precipitation series,
d is the average standard deviation of the normalised precipitation series.

Table 2 | Classification of precipitation conditions according to the standardised precipitation index SPI and corresponding probabilities

SPI	Period	Probability %
≤ -2.0	Extremely dry	2
[−2.00; −1.50)	Very dry	4
[−1.50; −0.50)	Dry	25
[−0.5; 0.5)	Normal	38
[0.5; 1.5)	Wet	25
[1.5; 2)	Very wet	4
≥ 2	Extremely wet	4

Discharge and physicochemical properties

The discharge of each spring was measured using the volumetric method (measuring the time of filling up a container of known volume. By dividing the volume by the time, discharge can be calculated), while the pH, EC of the water and water temperature were recorded on site using a high precision multi-parameter CX-401 meter, made by Elmetron (accuracy 0.002 pH; ±0.01 mV). All measurements were made in the field at all the springs mapped during the study. The newly created data set (containing the coordinates of springs collected in the field) combined with geographic information system techniques were used to map the locations of perennial and temporal springs. Changes in the spring density index, total spring yield and physicochemical properties of the water were analysed. The density of springs is expressed by the spring density index and it specifies the number of springs per unit area (km^{-2}). In order to determine the coefficient of variation of the number of springs mapped in each of the catchments, as well as the minimum, average and maximum discharge values and physicochemical parameters between measurement series, coefficients of variation (C_v) were calculated and expressed as a percentage following the formula:

$$C_v = \frac{S*100}{M}$$

where:

S is the standard deviation and
M is the arithmetic average,

with the following brackets: <20%, low variability; 20–40%, average variability; 40–100%, high variability; 100–150%, very high variability; >150%, extremely high variability.

RESULTS

Catchment characteristics

The amount of precipitation at the time of the research (in the hydrological year 2013) ranged from 841 mm for the year^{-1} at the outpost in Słoszów (556 m a.s.l.) to 1,088 mm for the year^{-1} at the station in Zieleniec (900 m a.s.l., Figures 1 and 2). The highest levels of around 120 mm per month^{-1} were recorded in May, June and September, while the lowest precipitation occurred in April (20–40 mm in a month^{-1}). Each mapping was carried out in months with precipitation amounts lower (November 2012 45–55 mm in a month^{-1}; July 2013 50–70 mm month^{-1}; October 2013 38–50 mm in a month^{-1}) than average recorded in the 1891–1930 period (November 70–95 mm month^{-1}; July 125–145 mm in a month^{-1}; October 85–110 mm in a month^{-1}). However, the assessment of rainfall conditions in the study area points to the year 2013 as experiencing a slightly lower amount of precipitation (841–1,088 mm) than the annual average (996–1,223 mm).

The SPI method was used to carry out analyses of rainfall levels at stations located within the catchment or in its immediate vicinity. The data shown (Figure 3) indicate that in the study area, the years 2012 and 2013 experienced normal precipitation levels (the results fell within the range −0.5; 0.5) for all the years studied (1996–2013). Also precipitation levels in the year preceding the hydrological year 2013 were similar to the annual average.

In each catchment, between nine and 33 springs were mapped (Table 3). According to the classification system proposed by Springer & Stevens (2009), all the mapped springs are helocrene and rheocrene. The largest number of springs (on average 29) was recorded in the Podgórna catchment (No. 3, Figure 1), while the lowest number (on average 10.6) was noted in the catchment of Mostowy

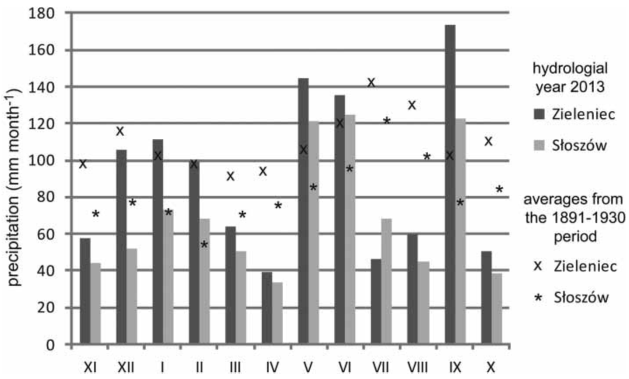

Figure 2 | Precipitation amount (hydrological year 2013) at meteorological stations located near the studied area.

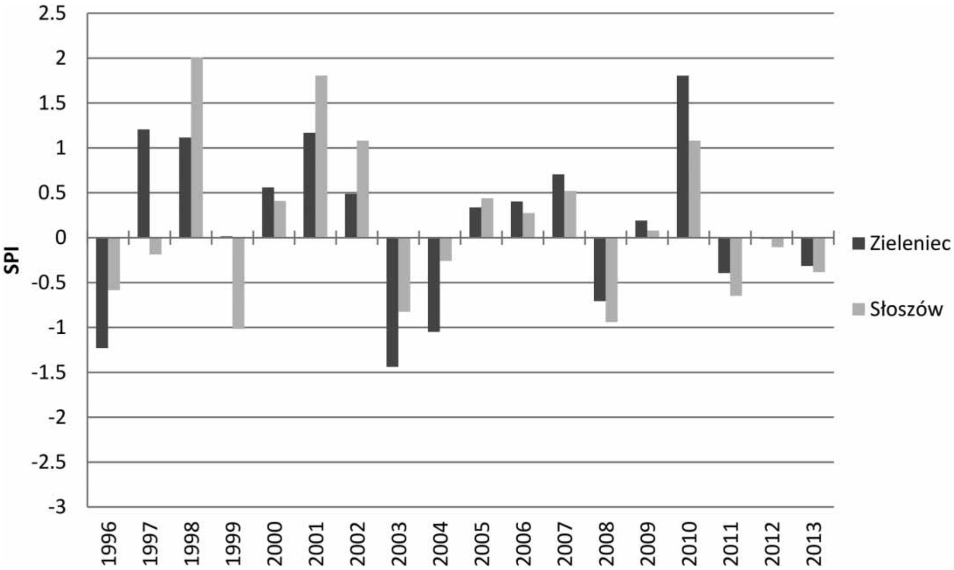

Figure 3 | Evaluation of precipitation conditions in years 1996–2013 based on the SPI classification.

Stream (No. 4). In the case of Machowski Stream and Inflow at the foot of Mount Grodziec, the figures were 14 and 20.6 respectively. In November 2012 and July 2013, the number of mapped springs in each of the catchments was similar, although a significant decrease in their number and density was observed in October 2013. The smallest variation in the number of springs was observed in gentle catchments ($C_v = 7–14\%$), while the coefficient of variation in their steep counterparts reached 31% (Machowski Stream).

The spring density index relates to the number of mapped springs and in this case falls between 2.5 and 9.4 springs per km^2. The lowest values were recorded in the catchment of Mostowy Stream and the highest in the Podgórna catchment (Table 3). In the other two catchments the index ranged from 2.8 to 5.2 and its variability was lowest in the Inflow at the foot of Mount Grodziec catchment (4.3–4.9).

Even though hydrogeological mapping was carried out each time when there were similarly low groundwater levels, temporal springs were recorded in all of the catchments (Table 3; Figure 1). Their numbers ranged from three (Inflow at the foot of Mount Grodziec and Mostowy Stream) to as many as 10 (Podgórna). A relatively high number of temporal springs (eight) was found in the Machowski Stream catchment. Temporal springs constitute between 13.6 and 47.1% of the springs mapped.

Discharge

Despite the similar surface areas of the catchments, the highest spring yield was recorded in July 2013 in the

Table 3 | The number of mapped springs and the spring density index computed in each measurement series

Catchment no. (see Table 1)	Geology	Number of springs			Springs density index (km^{-2})			C_v (%)	Number of periodic springs
		Nov-12	July-13	Oct-13	Nov-12	July-13	Oct-13		
1	Compact sedimentary rocks	17	16	9	5.2	4.9	2.8	31	8
2		22	21	19	4.9	4.7	4.3	7	3
3	Crystalline rocks	31	33	23	8.9	9.4	6.6	18	10
4		11	12	9	3.1	3.4	2.5	14	3

Table 4 | Total spring yield recorded during given measurement series

Catchment no. (see Table 1)	Geology	Spring specific discharge ($l\ s^{-1}\ km^{-2}$) Nov-12	July-13	Oct-13	Total spring yield ($l\ s^{-1}$) Nov-12	July-13	Oct-13	C_v (%)
1	Compact sedimentary rocks	1.75	2.33	1.34	5.78	7.68	4.41	34
2		2.54	3.36	1.69	11.44	15.12	7.6	40
3	Crystalline rocks	3.63	6.51	2.04	12.71	22.77	7.13	63
4		2.32	3.03	1.23	8.36	10.92	4.41	49

Podgórna catchment ($22.8\ l\ s^{-1}$), while the lowest discharge ($4.4\ l\ s^{-1}$) was recorded in October of the same year in the Machowski Stream and Mostowy Stream catchments (Table 3). These numbers correspond to the specific discharge, which ranged from $1.35\ l\ s^{-1}\ km^{-2}$ (autumn 2013, Machowski Stream) to $6.5\ l\ s^{-1}\ km^{-2}$ (summer 2013, Podgórna) and do not correlate with the height at which the catchment located. The lowest average spring specific discharge was quoted for catchments 1 and 4, the catchments which are located at the lowest (catchment 1) and the highest (catchment 4) altitudes. The temporal coefficient of variation of total spring discharge indicates an average ($C_v = 34\%$ Machowski Stream) to high ($C_v = 40–63\%$ other catchments) variability (Table 4). Catchments composed of crystalline rocks show greater variations in total spring yield (high variability) than those made up of compact sedimentary rocks (average/high variability).

The discharge of individual springs varied between 0.01 and $5\ l\ s^{-1}$ (Figure 4). Average discharge depended on the study area and the time of mapping, ranging from 0.34–$0.49\ l\ s^{-1}$ in Machowski Stream to 0.49–$0.91\ l\ s^{-1}$ in Mostowy Stream. In all the catchments, spring discharge was lowest in October 2013 (Table 4), which was also the month with the lowest number of identified springs (Table 3). The catchment of Mostowy Stream proved an exception: in October 2013, low-discharge springs within the area were classified as dry, with a lowest recorded yield of just $0.08\ l\ s^{-1}$.

Low discharges experienced the greatest variations (Table 5), with the coefficient of variation falling between 54 and 103% (high and very high variability). In all of the catchments, the variability of medium and high discharges was classified as either low or average ($C_v = 19–35\%$). Only in the Podgórna catchment did the Q_{max} coefficient of variation exceed 50%, indicating a high variability.

Taking terrain inclination into account (Table 1), the greatest variations in spring yield were recorded in the case of gentle catchments and low discharges ($C_v = 88$ and 103%). In steep catchments it was the high discharges ($C_v = 33$ and 52%) that experienced the greatest variability. In terms of lithology, catchments composed of crystalline rocks demonstrated a higher spring discharge variability (Table 5).

Physicochemical

The pH of spring water was between 3.47 and 8.60, classifying it as acidic to mildly alkaline. Minimum pH figures (3.47–4.07) were recorded in the catchment of Machowski Stream and did not depend on the time of mapping, whereas the lowest average pH was measured in the Mostowy Stream catchment (6.02–6.17, Figure 4). Springs in the Podgórna catchment proved to have the most alkaline reaction (8.49–8.60), irrespective of the time of mapping.

The greatest variations of pH were recorded in the case of pH_{min} (Table 5). The coefficient of variation of the lowest pH levels ranged from 6 (Podgórna) to 12% (Inflow at the foot of Mount Grodziec), based on the data collected in the catchments in three measurement series. Catchments composed of compact sedimentary rocks saw marked variations in the pH of groundwater. There appears to be no relation between the variability coefficient of pH and the morphological diversity of the catchment (Table 5).

The EC of the water ranged from 39.2 to 522 μS/cm (Figure 4). The lowest values were recorded in the catchment area of Mostowy Stream, regardless of the time of mapping. The lowest conductivity had a coefficient of

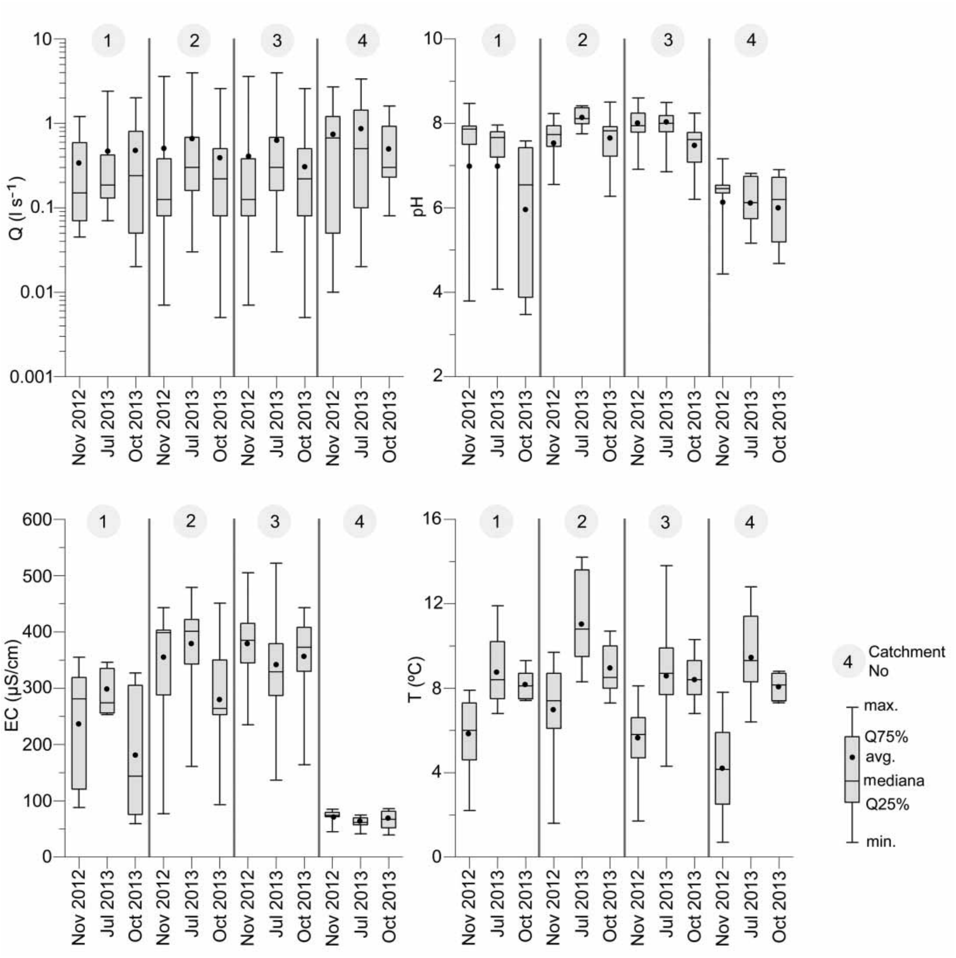

Figure 4 | Physicochemical parameters recorded during three measurement series. Q – spring discharge, pH – water reaction, EC – electrolytic conductivity of water, T – temperature of water.

variation ranging from 7 (Mostowy Stream) to 79% (Machowski Stream), depending on the time of mapping (Table 5). A relatively high variability of minimal conductivity was observed in the Inflow at the foot of Mount Grodziec catchment, where the figures recorded in November 2012 and July 2013 were 76.8 µS/cm and 161.0 µS/cm ($C_v = 41\%$) respectively. High conductivity saw the smallest variations (between 4 and 9%). The variability of EC was higher in catchments composed of compact sedimentary rocks. During the research, the temperature of the spring water ranged from 0.7°C to 14.2°C (Figure 4). The 0.7°C figure was quoted for a spring with a very low discharge, during a period of consistently low air temperatures and ground frost. The coefficient of variation of minimum temperatures was dependent on the time of mapping and ranged from 52 to 75%, indicating a high variability of this parameter. In the case of low and average temperatures, a greater variability was observed in gentle catchments and catchments composed of crystalline rocks (Table 5).

DISCUSSION

Scientific publications (Bryan 1919; Michalczyk 1997; Pacheco & Alencoão 2002; Onda *et al.* 2006; Oliveira *et al.* 2014; Mostowik *et al.* 2016) point to the number and discharge of springs, as well as the regime of the water's physicochemical parameters as important hydrogeological indicators that allow for an in-depth characterisation of groundwater flow (which means precipitation water which

Table 5 | The coefficient of variation [in %] of spring discharge and physicochemical parameters

Catchment no. (see Table 1)	**Compact sedimentary rocks**		**Crystalline rocks**	
Geology	**1**	**2**	**3**	**4**
Q_{min}	54	88	87	103
Q_{avg}	19	30	42	30
Q_{max}	33	21	52	35
pH_{min}	8	12	6	8
pH_{avg}	10	4	4	1
pH_{max}	6	2	2	3
EC_{min}	79	41	28	7
EC_{avg}	25	15	6	8
EC_{max}	4	4	9	8
T_{min}	52	63	60	75
T_{avg}	21	23	24	36
T_{max}	21	21	27	27

Q – discharge, pH – acidity, EC – electrolytic conductivity, T – temperature, min – minimal, avg – average, max – maximal.

has been absorbed by the ground and has become part of the groundwater, alternately begin discharged as springs and seepage water into the streams channels and leaving no drainage as runoff). The high temporal variability of those features is natural, particularly in mountainous regions and a number of geological and hydrogeological factors must be taken in groundwater potential mapping (Naghibi & Dashtpagerdi 2017).

Catchment characteristic

Having analysed the distribution of springs in the Lublin Upland and Roztocze, Michalczyk (1997) came to the conclusion that the number of springs in a particular area cannot be precisely determined, and spring discharge varies greatly depending both on the time and on the characteristics of the catchment. Hydrological research on the basalt landscape in the Oregon Cascade Range area also showed, that the density of springs drop from 0.07 per km^2 on Quaternary basalts to zero on Pliocene–Miocene basalts (Jefferson *et al.* 2010). Within Quaternary units there is no relationship between the age of the basalt and spring density. Drużkowski (2000) found that the variability of the spring density index in the Wierzbówka catchment (in the Carpathian Foothills) was quite significant, ranging from 0.6 to 14 springs per km^2, depending on the time of mapping. The number of springs was largest (164) in early spring (March–April) and declined by about 30–40% towards the beginning of summer (Drużkowski 2000). During the autumnal low groundwater level, only five to 12 springs were active (water was still flowing from a rock upon the land). The results of the spring density index for the freshwater springs occurring in the crystalline and compact sedimentary rocks in the Sudeten Mountains showed less extreme variations in the number of springs than those reported by Drużkowski (2000), because seasonal springs, such as those appearing after the spring melt or as a result of heavy rainfall, are not included in the current research. Despite this and the fact that the measurements were only taken during the low groundwater flow, the number of springs varied by as much as 31%, but in the case of the distribution and density of springs, due to incomplete knowledge that exists for most regions, errors cannot be ruled out (Junghans *et al.* 2016).

Discharge and physicochemical

According to Drużkowski (2000), average spring discharge in the Wierzbówka catchment fell to 0.1–0.2 l s^{-1}, with a maximum of 5 l s^{-1} (after heavy rainfall). When analysing changes in the physicochemical properties and chemical composition of springs in the Tatras, Małecka (1997) and Żelazny *et al.* (2011, 2013) similarly noted temporal and spatial variability directly associated with the geological and tectonic structure of the area. They found that during the 1979–1990 period, the difference between the minimum and maximum yields of karst springs was more than 10-fold ($Q_{min} = 65$ l s^{-1}; $Q_{avg} = 321$ l s^{-1}; $Q_{max} = 4{,}110$ l s^{-1}) and the coefficient of variation of pH in the year 2009 fell to 1.2–4.8%, depending on the site. In the case of conductivity, the variability of concentrations ranged from 6.2 to 14.2%, while water temperature deviations reached 12.6%. Wolock *et al.* (1997) have also offered a hypothesis that spatial variations in stream chemistry reflect increased subsurface contact time with increasing basin area, as determined by variations of surface topography and estimated changes in soil hydraulic conductivity. Shaman *et al.* (2004) suggest that stream runoff (particularly at baseflow) is instead controlled largely by the integration of shallow subsurface macropores and bedrock fractures.

Results produced during this research similarly indicated a high variability of the discharge regime and physicochemical parameters. The coefficient of variability in the case of the total spring discharge ranged from 34 to 63% and minimum discharges up to 103%. Higher spring discharge variability was observed in the catchments consisting of crystalline rocks. This confirms the results obtained by Moniewski (2015), who found that springs originating in fissure rock had the most irregular and changeable discharges.

In terms of the water's physicochemical parameters, variability was lowest in the case of pH (as noted by Żelazny *et al.* 2013) but quite high in the case of the EC of the water and temperature, occasionally reaching 75–79%. Nonetheless, the highest variability was observed in the case of minimum conductivity and temperature; in the case of average and maximum levels, the variability was closer to the results received in the Tatras.

Hydrogeological research (Michalczyk 1997) indicates that in low-permeable rocks the water table is more inclined and spring discharge usually low, while in high-permeable rocks characterised by numerous cracks and fissures the springs tend to have high and regular discharges. Onda *et al.* (2006) suggest that the subsurface storm flow is dominant even in extremely steep mountainous areas and that the subsurface flow through the soil mantle is dominant in granite watersheds, whereas bedrock flow is dominant in shale watersheds. Results from the measurements of spring discharges and their variability were in keeping with the findings reported by Michalczyk (1997), indicating higher spring discharges in catchments composed of crystalline rocks. Nonetheless, springs located in these catchments had less stable discharge and their number was subject to considerable variation. These findings show that in the area under study, high spring discharges were not necessarily more regular.

The spring hydrological profile developed in this paper, covering areas composed of compact sedimentary rocks and crystalline rocks, seems to indicate that groundwater flow (spring recharge) in sedimentary rocks is more diffuse, which accounts for the springs' lower, but more stable discharges. In crystalline rocks springs had higher and more variable discharges, which points to less aquifer storage capacity and, at the same time, greater conductivity. These findings are consistent with the results of laboratory tests and lineament analyses of crystalline and compact sedimentary rocks found in the Polish Sudetes (Bażyński *et al.* 1986; Graniczny 1994; Tarka 2006). Tarka (2006) established that compact sedimentary rocks can store large amounts of water due to their high porosity. The open porosity ratio of sandstone reaches 28%, while in the case of marl and mudstone the figure does not exceed 27%, with an arithmetic mean of 17 and 9%, respectively. At the same time open porosity ratio points towards a high storage coefficient (on average 0.103) and coefficient of hydraulic conductivity (on average $5.93 \cdot 10^{-6}$ m/s). The porosity of crystalline rocks normally ranges from 0.1 to 3%, reaching 5–7% under optimum conditions (Staśko 2002), while the storage coefficient tends to fall between 0.008 and 0.05. The coefficient of hydraulic conductivity in the case of crystalline rocks reaches on average $1.15 \cdot 10^{-5}$ m/s. Discrepancies between spring regime and the geology or complex tectonic structure are indicative of a high local variability of drainage basins in the Sudeten Mountains. This would support the hypothesis about the coexistence of recharge zones within drainage areas. Therefore, it can be argued that drawing conclusions based on periodic, rarely performed measurements or transferring results from neighbouring drainage basins carries a high risk of error. The results obtained in other mountain ranges frequently highlight these variations and discrepancies: Pacheco & Alencoão (2002) or Asano & Uchida (2012) and Allen & Chapman (2001) have demonstrated that the depth of hydrologically active soil and bedrock and vegetation, grassland and forests in particular, have a profound effect on infiltration and spring specific discharge or groundwater runoff.

CONCLUSION

The springs mapped in the four test catchments are helocrene and rheocrene of yields ranging from 0.01 to 1 l s^{-1}. The pH, temperature and the conductivity of the water did not deviate from those recorded in other areas of the Sudetes. The spring density index varied from 2.8 to 9.4 springs/km^2, also falling within the range considered normal for this region. Detailed data analysis has nevertheless shown that the time of research can have a significant impact on the results. In most cases, the ratio of the number, discharge and physicochemical properties of springs had average to high variability. Other factors affecting the results included terrain morphology and the lithology of rocks in the substratum.

In steep catchments, the spring density index was higher and springs were more numerous. At the same time steep catchments in comparison to gentler slope catchments are characterised by greater variability of the number of springs. There was also a greater variation in EC and discharge of springs. The study did not show a direct relation between pH level and the morphological diversity of the catchment. The analysis of the spring discharge ratio indicates a higher variability in the case of springs originating in crystalline rocks ($C_v = 49–63\%$), with minimum discharges showing the greatest variations ($C_v = 54–103\%$). The variability ratio for spring water temperature was higher in the case of the springs found in crystalline rocks ($C_v = 24–75\%$), while an elevated variability ratio for pH ($C_v = 2–12\%$) and conductivity ($C_v = 4–79\%$) was registered in catchments composed of compact sedimentary rocks. The measurements of the physicochemical parameters of the water also point towards the variability ratio being highest for the minimum values (pH_{min}, EC_{min}, T_{min}).

Further studies will need to be carried out in order to estimate the coefficient of variation between each catchment. Spatial comparison will enable to us gain more detailed knowledge about processes and connectivity. The issue facing the author will be to determine the variations in the physicochemical properties of springs depending on the discharge of the spring and will be supported by relevant statistical analyses.

ACKNOWLEDGEMENTS

This work was financed by the National Science Centre based on decision number DEC-2011/01/B/ST10/05121. Data regarding amounts of precipitation were made available by the IMGW-PIB. The author of this paper would like to extend special thanks to Magdalena Modelska, Marek Wcisło, Lidia Kasperczyk and Moath Almaaitah for their time, commitment and support during fieldwork, and to the Institutes for providing financial support and meteorological data. I wish to thank the reviewers and co-editor for their detailed comments, which were invaluable in the editing process and in understanding methods relevant to temporal variability of spring. Suggestions made by the reviewers were very helpful in the process of eliminating errors and imperfections in the first version.

REFERENCES

Allen, A. & Chapman, D. 2001 Impact of aforestation on groundwater resource and quality. *Hydrogeology Journal* **9**, 121–142.

Asano, Y. & Uchida, T. 2012 Flow path depth is the main controller of mean base flow transit times in a mountainous catchment. *Water Resour. Res.* **48**, W03512. doi:10.1029/2011WR010906.

Bartnik, A. & Walisch, M. 1997 Źródła zlewni Bystrzycy Dusznickiej [Springs of the Bystrzyca Dusznicka drainage basin]. *Acta Univ. Lodz., Folia Geogr. Phys.* **2**, 61–72.

Bażyński, J., Graniczny, M., Oberc, J. & Wilczyński, M. S. 1986 *Mapa fotogeologiczna Sudetów 1:200 000 [Photogeological map of Sudetes]*, Wyd. Geol., Warszawa.

Bense, V. F., Gleeson, T., Loveless, S. E., Bour, O. & Scibeck, J. 2013 Fault zone hydrogeology. *Earth-Science Reviews* **127**, 171–192.

Bryan, K. 1919 Classification of springs. *The Journal of Geology* **27** (7), 522–561.

Buczyński, S. & Rzonca, B. 2011 Effects of crystalline massif tectonics on groundwater origin and catchment size of a large spring area in Zieleniec, Sudety Mts., SW Poland. *Hydrogeology Journal* **19**, 1085–1101.

Buczyński, S., Modelska, M., Olichwer, T., Tarka, R. & Staśko, S. 2011 Charakterystyka krenologiczna masywów górskich Ziemi Kłodzkiej na podstawie bazy danych "Źródło" [Spring hydrogeology of mountainous areas of Kłodzko region on the basis "Spring" database]. *Biuletyn PIG* **445**, 17–26.

Chełmicki, W., Jokiel, P., Michalczyk, Z. & Moniewski, P. 2011 Distribution, discharge and regional characteristics of springs in Poland. *Episodes* **34** (4), 244–256.

Ciężkowski, W., Schmalz, A. & Żak, S. 2001 Charakterystyka krenologiczna zlewni Kryniczanki w Beskidzie Sądeckim [Spring's characteristic of the Kryniczanka River catchment, Beskid Sądecki MTS (Carpatian)]. *Współczesne Problemy Hydrogeologii* X, 141–148.

Corsini, A., Cervi, F. & Ronchetti, F. 2009 Weight of evidence and artificial neural network for potential groundwater spring mapping: an application to the Mt. Modino area (Northern Apennines, Italy). *Geomorphology* **111**, 79–87.

Cymerman, Z. 1989 *Szczegółowa Mapa Geologiczna Sudetów w skali 1:25 000, Arkusz 900D – Duszniki Zdrój [Detailed Geological map of SudetyMountains, Scale 1:25000, Section900D 'Duszniki Zdrój']*. Państwowy Instytut Geologiczny i Wydawnictwa Geologiczne, Warsaw, Poland.

Cymerman, Z. 1991 *Szczegółowa Mapa Geologiczna Sudetów w skali 1:25 000, Arkusz 900C – Lewin Kłodzki [Detailed Geological map of SudetyMountains, Scale 1:25000, Section900C 'Lewin Kłodzki']*. Państwowy Instytut Geologiczny i Wydawnictwa Geologiczne, Warsaw, Poland.

Drużkowski, M. 2000 Variability of natural effluents as an indicator of groundwater retention in the Carpathian foothills (southern Poland). *Environ. Geol.* **40**, 90–98.

Earman, S., McPherson, B. J. O. L., Phillips, F. M., Ralser, S., Herrin, J. M. & Broska, J. 2008 Tectonic influence on ground water quality: insight from complementary methods. *Ground Water* **46** (3), 354–371.

Gierwielaniec, J. & Radwański, S. 1955 *Szczegółowa Mapa Geologiczna Sudetów w skali 1:25 000, Arkusz 900A – Jeleniów [Detailed Geological map of SudetyMountains, Scale 1:25000, Section900A 'Jeleniów']*. Państwowy Instytut Geologiczny i Wydawnictwa Geologiczne, Warsaw, Poland.

Graniczny, M. 1994 *Strefy nieciągłości tektonicznych w świetle korelacji wielotematycznych danych geologicznych na przykładzie okolic Żarnowca i Ziemi Kłodzkiej [Tectonic zones in Terms of the Geological Data Correlation on the Example of Żarnowiec and Kłodzko regions]*, Instrukcje i Metody Badań Geolog., PIG, Warszawa, p. 54.

Grocholski, A. 1956 *Szczegółowa Mapa Geologiczna Sudetów w skali 1:25 000, Arkusz 932B – Mostowice [Detailed Geological map of SudetyMountains, Scale 1:25000, Section932B 'Mostowice']*. Państwowy Instytut Geologiczny i Wydawnictwa Geologiczne, Warsaw, Poland.

Jefferson, A., Grant, G. E., Lewis, S. L. & Lancaster, S. T. 2010 Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA. *Earth Surf. Process. Landforms* **35**, 803–816.

Junghans, K., Springer, A. E., Stevens, L. E., Jeri, D. & Ledbetter, J. D. 2016 Springs ecosystem distribution and density for improving stewardship. *Freshwater Science* **35** (4), 1330–1339.

Łabędzki, L. 2006 Susze rolnicze. Zarys problematyki oraz metody monitorowania i klasyfikacji [Agricultural drought. Overview problems and methods for monitoring and classification]. *Water-Environment-Rural Areas* **17**, p. 107.

Małecka, D. 1997 Źródła masywu tatrzańskiego [Spring of the Tatra Massif]. *Acta Universitatis Lodziensis. Folia Geographica Physica* **2**, 9–25.

Manga, M. 2001 Using springs to study groundwater flow and active geologic processes. *Annu. Rev. Earth Planet. Sci.* **29**, 201–228.

McKee, T. B., Doesken, N. J. & Kleist, J. 1995 Drought monitoring with multiple time scales. In: *Preprints of 9th Conf. of Applied Climatology*, 15–20 January, Dallas, Texas, pp. 233–236.

Michalczyk, Z. 1997 Źródła wyżyny Lubelskiej i Roztocza [Springs of the Lublin upland and the Roztocze]. *Acta Universitas Lodziensis, Folia Geographica Physica* **2**, 73–93.

Mocior, E., Rzonca, B., Siwek, J., Plenzler, J., Płaczkowska, E., Dąbek, N., Jaśkowiec, B., Potoniec, P., Roman, S. & Zdziebko, D. 2015 Determinants of the distribution of springs in the upper part of a flysch ridge in the Bieszczady Mountains in southeastern Poland. *Episodes* **38** (1), 21–30.

Moniewski, P. 2015 Seasonal variability of discharge from selected springs in Central Europe. *Episodes* **38** (3), 189–196.

Mostowik, K., Górnik, M., Jaśkowiec, B., Maciejczyk, K., Murawska, M., Płaczkowska, E., Rzonca, B. & Siwek, J. 2016 High discharge springs in the Outer Flysch Carpathians on the example of the high Bieszczady Mountains (Poland). *Carpathian Journal of Earth and Environmental Sciences* **11** (2), 395–404.

Naghibi, S. A. & Dashtpagerdi, M. M. 2017 Evaluation of four supervised learning methods for groundwater spring potential mapping in Khalkhal region (Iran) using GIS-based features. *Hydrogeol J.* **25**, 169–189.

Oliveira, A. S., Silva, A. S., Mello, C. R. & Alves, G. J. 2014 Stream flow regime of springs in the Mantiqueira Mountain Range region, Minas Gerais State. *Cerne* **20** (3), 343–349.

Onda, Y., Tsujimura, M., Fujihara, J. & Ito, J. 2006 Runoff generation mechanisms in high-relief mountainous watersheds with different underlying geology. *Journal of Hydrology* **331**, 659–673.

Ozdemir, A. 2011 GIS-based groundwater spring potential mapping in the Sultan Mountains (Konya, Turkey) using frequency ratio, weights of evidence and logistic regression methods and their comparison. *Journal of Hydrology* **411**, 290–308.

Pacheco, F. A. L. & Alencoão, A. M. P. 2002 Occurrence of springs in massifs of crystalline rocks, northern Portugal. *Hydrogeology Journal* **10**, 239–253.

Pawlak, W. (ed.) 1997 *Atlas Śląska Dolnego i Opolskiego [The Atlas of the Lower Silesia and Opole Silesia]*. Wydawnictwo Uniwersytetu Wrocławskiego, Wrocław, Poland.

Shaman, J., Stieglitz, M. & Burns, D. 2004 Are big basins just the sum of small catchments? *Hydrol. Process.* **18**, 3195–3206.

Springer, A. E. & Stevens, L. E. 2009 Spheres of discharge of springs. *Hydrogeology Journal* **17** (1), 83–93.

Staśko, S. 2002 Zawodnienie szczelinowych skał krystalicznych w Sudetach [Water in fissured crystalline rocks in the Sudety Mountains]. *Biuletyn PIG* **404**, 249–262.

Staśko, S. & Tarka, R. 2002 *Zasilanie i drenaż wód podziemnych w obszarach górskich na podstawie badań w Masywie S nieżnika [Groundwater Recharge and Drainage Processes in Mountainous Terrains Based on Research in the Śnieżnik Massif (Sudetes, SW Poland)].* Seria "Hydrogeologia", Acta Universitatis Wratislaviensis 2528, Wrocław, Poland.

Tarka, R. 2006 *Hydrogeologiczna charakterystyka utworów kredy w polskiej części Sudetów [Hydrogeological Characteristic of the Cretaceous Sediment in Polish Part of the Sudety Mts.].* Acta Universitatis Wratislaviensis, 2884, Wrocław.

Waksmundzki, K. 1972 *Wpływ środowiska geograficznego na charakter wypływów wody podziemnej w źródłowej części zlewni Wisły [The Impact of the Geographical Environment on the Nature of the Groundwater Outflows in the Spring Section of the Vistula Catchment]*. Arch. Inst. Geogr. UJ, Kraków.

Wolock, D. M., Fan, J. & Lawrence, G. B. 1997 Effects of basin size on low-flow stream chemistry and subsurface contact time in the Neversink River watershed, New York. *Hydrological Processes* **11**, 1273–1286.

Żelazny, M., Astel, A., Wolanin, A. & Małek, S. 2011 Spatiotemporal dynamics of spring and stream water chemistry in a high-mountain area. *Environmental Pollution* **159**, 1048–1057.

Żelazny, M., Barczyk, G., Wolanin, A. & Wójcik, S. 2013 Zmiany cech fizyczno-chemicznych wód wywierzysk: Chochołowskiego, Lodowego i Olczyskiego w 2009 r. [Changes in physical and chemical characteristics of Chochołowskie, Lodowe and Olczyskie vaucluse springs in 2009]. *Biuletyn PIG* **456**, 685–692.

First received 24 August 2016; accepted in revised form 21 August 2017. Available online 9 November 2017