Carpathian Journal of Earth and Environmental Sciences, August 2016, Vol. 11, No 2, p. 395 - 404

HIGH DISCHARGE SPRINGS IN THE OUTER FLYSCH CARPATHIANS ON THE EXAMPLE OF THE HIGH BIESZCZADY MOUNTAINS (POLAND)

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Abstract: Hydrogeological properties and hydrometeorological conditions determine spring discharge, which is usually very low (<0.5 L s^{-1}) in the Outer Carpathians. The study presents eight high discharge springs in the Polonina Wetlinska Massif in the Bieszczady Mountains (SE Poland) located on the northern slopes at high elevations near the ridgeline. The average discharge of the studied springs ranged from 1.2 to 8.5 L s^{-1} but under favorable hydrometeorological conditions they may reach 20 L s^{-1}. The detection of discharge during extreme drought confirmed the presence of seven (out of eight) permanent springs which is an evidence for relatively capacious groundwater reservoirs in Otryt sandstones following the NE dip. Enlargement of spring recharge areas in relation to small topographic catchments is caused by the direction of faults and fissures and flow paths following the strike direction of rock layers (the ridgeline of Polonina Wetlinska).

Key words: spring discharge, Outer Flysch Carpathians, groundwater reservoirs, recharge mechanisms, regional hydrogeology

1. INTRODUCTION

Spring discharge is determined by a variety of elements of the natural environment. In the temperate climate zone, the most important environmental element is geology, especially hydrogeological properties of rocks and local tectonic patterns that determine groundwater circulation conditions. Spring discharge is also strongly linked with both short-term and long-term changes in the hydrometeorological situation. The flysch rocks that constitute the Outer Carpathians are characterized by low values of filtration parameters and a low water storage capability. This result is a large number of very low discharge springs – usually under 0.5Ls^{-1} (Jokiel, 1997; Dynowska & Pociask-Karteczka, 1999; Chowaniec, 2002; Chowaniec & Witek, 2002a, 2002b; Witek, 2002; Buczyński et al., 2007; Lasek, 2008; Chełmicki et al., 2011).

Springs discharging several liters of water per second are rarely encountered in flysch areas. This is also true in the Bieszczady Mountains in southeastern Poland, although relatively few springs have been studied in the region and elsewhere in the flysch Carpathians in Poland. A small number of areas in the Bieszczady Mountains have been mapped in terms of springs and the results are available in the following research papers: Łajczak, 1996; Bogusz, 2004; Żurek, 2005; Rzonca et al., 2008, Łajczak et al., 2010; Lasek et al., 2012; Mocior et al., 2015. A few additional springs were also surveyed, as they are found close to residential areas and serve as sources of water for local residents (Chowaniec, 2002; Chowaniec & Witek, 2002a, 2002b; Witek, 2002). High discharge springs, defined as springs discharging more than one liter of water per second, constitute between 2.5% and 5.9% of all surveyed springs in the studied parts of the Bieszczady Mountains, depending on catchment (Bogusz, 2004; Żurek, 2005; Rzonca et al., 2008; Mocior et al., 2015).

High discharge springs are rare in the Bieszczady Mountains and constitute very valuable research sites. The observation of both high discharge and low-discharge springs is helpful in the study of water circulation patterns and residence times. It also helps quantify the supply of groundwater in a study area. This paper is based on an analysis of the discharge of eight springs in the Polonina Wetlinska Massif in the High Bieszczady Mountains. This is a particularly interesting group of springs, and not merely due to the high discharge rate. The location of these springs is quite atypical – high elevations near the ridgeline. Hence, it seems that it would be difficult to produce a high discharge spring at such a high elevation due to the limited recharge area. It must be that their high discharge is due to some atypical mechanism of recharge.

The purpose of the paper is to show the High Bieszczady Mountains in southeastern Poland, a mountain region in the Outer Flysch Carpathians, as a region characterized by the presence of high discharge springs. The paper analyzes vital hydrogeological conditions, especially recharge mechanisms that help produce high discharge springs in the study area. The high discharge springs used in this study were identified during the Polonina Wetlinska spring mapping project in 2010–2012 (Mocior et al., 2015) and have been since observed.

2. STUDY AREA

The study area is located in the High Bieszczady Mountains, which are part of the Outer Eastern Carpathians (Balon et al., 1995). The studied mountains are formed of flysch found across the Dukla and Silesian structural units. The study area is known as Polonina Wetlinska Massif and the entire area is built of Krosno Beds of the Silesian structural unit. It includes two sandstone and shale complexes – a lower complex (Lower Krosno Beds) and a middle complex (Otryt layers) (Fig. 1; Mastella & Tokarski, 1995).

The studied springs are located on the northern slopes of Polonina Wetlinska, an area part of Bieszczady National Park, at elevations ranging between 990 m and 1,130 m above sea level (Fig. 1). The area is characterized by the presence of thick layers of Otryt sandstone – up to 200 m thick (Haczewski et al., 2007).

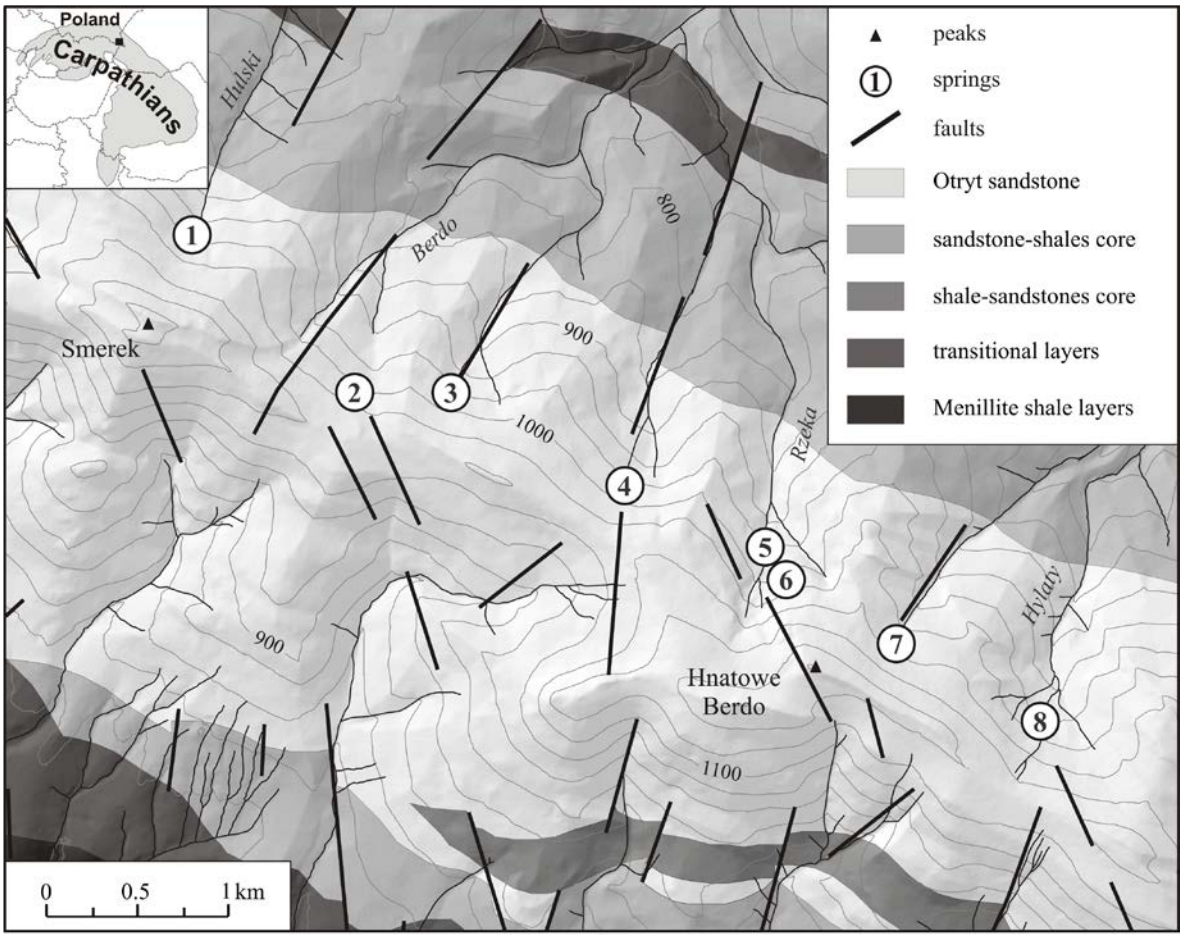

Figure 1. Location of studied springs superimposed on geological map (geological map after: Mastella & Tokarski, 1995)

The direction of the main ridge of Polonina Wetlinska is consistent with the strike of its rock layers (ESE–WNW). The layers dip consequently with the northern slopes of Polonina Wetlinska, where the investigated springs are located. Lateral ridges branch off from the main ridge at 90 degree angles and yield a step-type relief that reflects the resistance of each given rock layer, especially the presence of the thick resistant layers of Otryt sandstone.

Thick layers of Otryt sandstone form fissure-porous-type aquifers in the study area. The seepage of groundwater occurs mainly via fractures in sandstone whose porosity stands at a mere 2% to 6% (Królikowski & Muszyński, 1969). The low supply of groundwater is caused by limited retention capability in the permeable zone due to its small thickness (up to 40 m). The hydraulic conductivity is also low. Its value is assumed to be an average of $1.4 \cdot 10^{-6}$ m s^{-1} up to a depth of 20 m. Its value between 20 and 40 meters is $2.4 \cdot 10^{-7}$ m s^{-1} (Chowaniec et al., 1983).

It is important to note that the low hydraulic conductivity values that characterize Otryt sandstone most likely do not factor in the presence of fissures associated with local tectonics and other local features. The presence of such fissures may significantly increase rock permeability on a local basis. In the catchments of streams originating in Polonina Wetlinska, specific groundwater runoff ranges from 2.4 L s^{-1} km^{-2} to 6.8 L s^{-1} km^{-2} (Plenzler et al., 2010). The study area includes a number of fissure-type and debris-type springs (Rzonca et al., 2008, Mocior et al., 2015).

The Bieszczady Mountains are characterized by a mountain climate. The study area is located in a moderately cool vertical climatic zone (elevation: 650 to 1,075 m) as well as in a cool zone (elevations over 1,075 m). Atmospheric precipitation increases with elevation in the study area, ranging from 1,200 to 1,300 mm per year (Hess, 1965; Michna & Paczos, 1972; Paszyński & Niedźwiedź, 1999) or from 1,600 to 1,700 mm per year according to Laszczak et al., (2011). The highest precipitation occurs in summer.

The Polonina Wetlinska Massif features mostly Carpathian beechwood forest up to an elevation of about 1,150 meters (the timber line). Higher elevations feature only meadows (Winnicki & Zemanek, 2009).

3. METHODS

The paper is based on field discharge measurements for eight springs whose location was established and documented using GPS receivers. The fieldwork was done in the period 2010–2014 (Fig. 2).

All discharge measurements used in this paper were performed using the volumetric method. Every measurement cited in this paper is actually an arithmetic average of three field measurements whose statistical dispersion is adequately small. The magnitude of the statistical dispersion was evaluated using a modified relative error formula – the ratio of the difference between maximum and minimum values and the sum of maximum and minimum values.

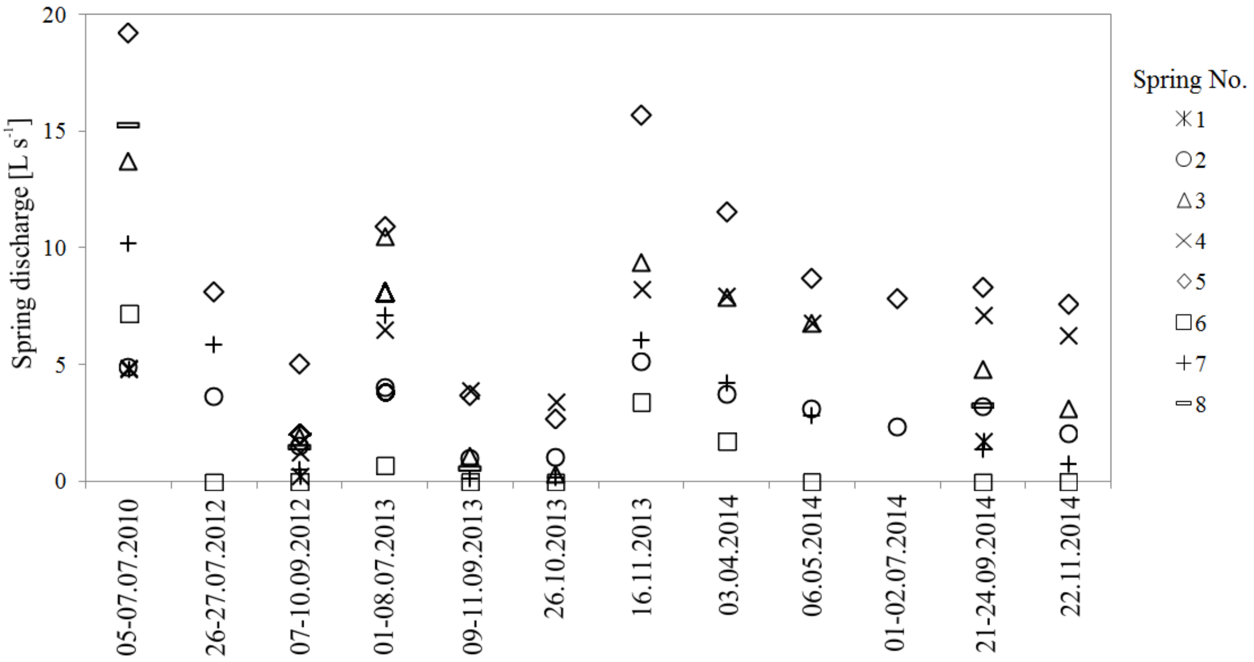

Figure 2. Spring discharge and dates of measurements in the period 2010-2014

Once three measurements were performed in the field whose relative error (statistical dispersion) did not exceed 5%, fieldwork at the given site was stopped, and an average was calculated. If the relative error exceeded 5%, then more measurements were performed. The elimination of extreme values (outliers) was performed in pairs – one highest value and one lowest value. This process continued until three acceptable values were obtained – values that were characterized by an adequately small statistical dispersion.

The procedure used to check the statistical dispersion of raw data makes it possible to virtually eliminate the effects of random errors occurring in the measurement process. It is highly likely that random errors do occur in the measurement process, as time intervals are measured using a stopwatch and the volume of water is measured using a volumetric vessel. The likelihood of random errors is actually a basic flaw of the research method used in this study. This is why it is important to maintain control over the reproducibility of the raw data.

It was often difficult to perform accurate discharge measurements in the study area due to local relief as well as the fact that the study area is located in a national park. The study was designed to minimize any harmful effects on the natural environment in the national park.

Measurements were performed with different frequency at each of the studied springs, which resulted in a different number of data points for each spring. Documented discharge values were used to calculate arithmetic discharge averages for each spring. Data were collected at various water stages in the study area. Fieldwork was performed for a long period of time including the autumn months of 2012 and 2013, which were characterized by very long periods of strong drought. Low water stages were noted for the San River at the Zatwarnica gauging site, which is the gauge station closest to the study area. Seven out of eight of the studied springs are located in the catchment of the San River gauged at Zatwarnica. Moreover, the Zatwarnica site is located at the edge of the highest region of the San catchment, which includes the High Bieszczady Mountains.

In the study, we assume that water stages measured at Zatwarnica represent a type of average of the hydrometeorological situation in the study area. Table 1 shows water stage data collected at Zatwarnica for days when spring discharge was measured in the study area during extremely dry periods of the hydrologic years 2012 and 2013. The magnitude of the drought in the autumn of 2013 was further confirmed by a change in the lowest of minimum annual water stages over the long term (absolute minimum) value (108 cm) for the Zatwarnica gauging site on September 17th. Other characteristic water stages at Zatwarnica were the average of minimum annual water stages over the long term is 116 cm, the highest of minimum annual water stages over the long term is 126 cm and the mean of average annual water stages over the long term is 141 cm.

Table 1. Water stages for the Zatwarnica gauging site during spring discharge measurements in the hydrological years 2012-2013

Date	Water stage [cm]
26.07.2012	162
27.07.2012	156
07.09.2012	116
08.09.2012	116
10.09.2012	116
01.07.2013	151
02.07.2013	144
08.07.2013	131
09.09.2013	114
10.09.2013	114
11.09.2013	112
26.10.2013	113

It is important to note that short-lasting changes in the hydrometeorological situation do not necessarily mean that low surface water stages will translate into low groundwater levels. However, droughts lasting several weeks tend to produce extremely low water stages in watercourses, and it is quite reasonable to assume that groundwater levels are at least low. This is especially true in the study area, which is characterized by very low groundwater retention capacity. Therefore, it is again reasonable to assume that springs that do not dry up even during periods of extreme drought, especially the record-breaking drought of September 2013, can be reliably assessed to be permanent springs.

Variances in spring discharge were quantified using Maillette's index of variability, which is the ratio of maximum discharge and minimum discharge. In this paper, this index is used to compare measured extreme values, although not necessarily absolute extremes noted for the entire study period. The reason for this is that the data used in the study are not part of a larger, continuous monitoring program, but only reflect random sampling values obtained in the course of consecutive measurement campaigns.

4. RESULTS

The studied springs are located on the northern slopes of Polonina Wetlinska (Fig. 1), just below the timberline. Most are found at elevations between 990 m and 1,050 m. Only two springs are located above 1,100 m. Of the eight springs studied, only Spring No. 2 is found on some tourist maps (Krukar, 2009). Spring No. 2 is located along the Yellow Tourist Trail that runs from the former village of Suche Rzeki to Orłowicz Pass.

In virtually all the studied cases, water exits the ground amidst debris on a slope. Only Spring No. 5 and Spring No. 7 were classified as fissure-debris-type springs. All eight studied springs were also classified as rheocrenes.

One of the studied springs is periodic (Spring No. 6, Table 2). It is located in the Rzeka Stream catchment (Fig. 3). This particular spring was found to be dry on multiple occasions, but sometimes it did produce a discharge of 1.7 $L\,s^{-1}$ or more; its discharge even exceeded 7 $L\,s^{-1}$ in some cases (Table 2). This one periodic spring was included in the study due to its occasionally high discharge.

The average discharge of the studied springs ranged from 1.2 Ls^{-1} to more than 8.5 Ls^{-1} (Table 2).

Table 2. Location and discharge characteristics of studied springs

No	Latitude	Longitude	Altitude	Topographic catchment area	Number of measurements	Discharge			Variability index max/min
						min	mean	max	
	[°]	[°]	[m.a.s.l.]	[ha]		[$L\,s^{-1}$]			
1	49 11.410	22 29.016	997	1.01	3	0.20	2.23	4.79	23.95
2	49 10.927	22 29.710	1029	1.81	14	1.02	2.95	5.12	5.02
3	49 10.912	22 30.141	998	2.36	11	0.25	6.13	13.72	54.88
4	49 10.616	22 30.900	995	3.70	10	1.24	5.63	8.23	6.64
5	49 10.416	22 31.515	1021	3.80	13	1.90	8.55	19.18	10.09
6	49 10.319	22 31.603	1049	1.93	11	0.00	1.19	7.24	-
7	49 10.115	22 32.081	1101	1.01	11	0.10	3.55	10.17	101.70
8	49 09.865	22 32.703	1123	1.34	4	0.57	5.14	15.27	26.79

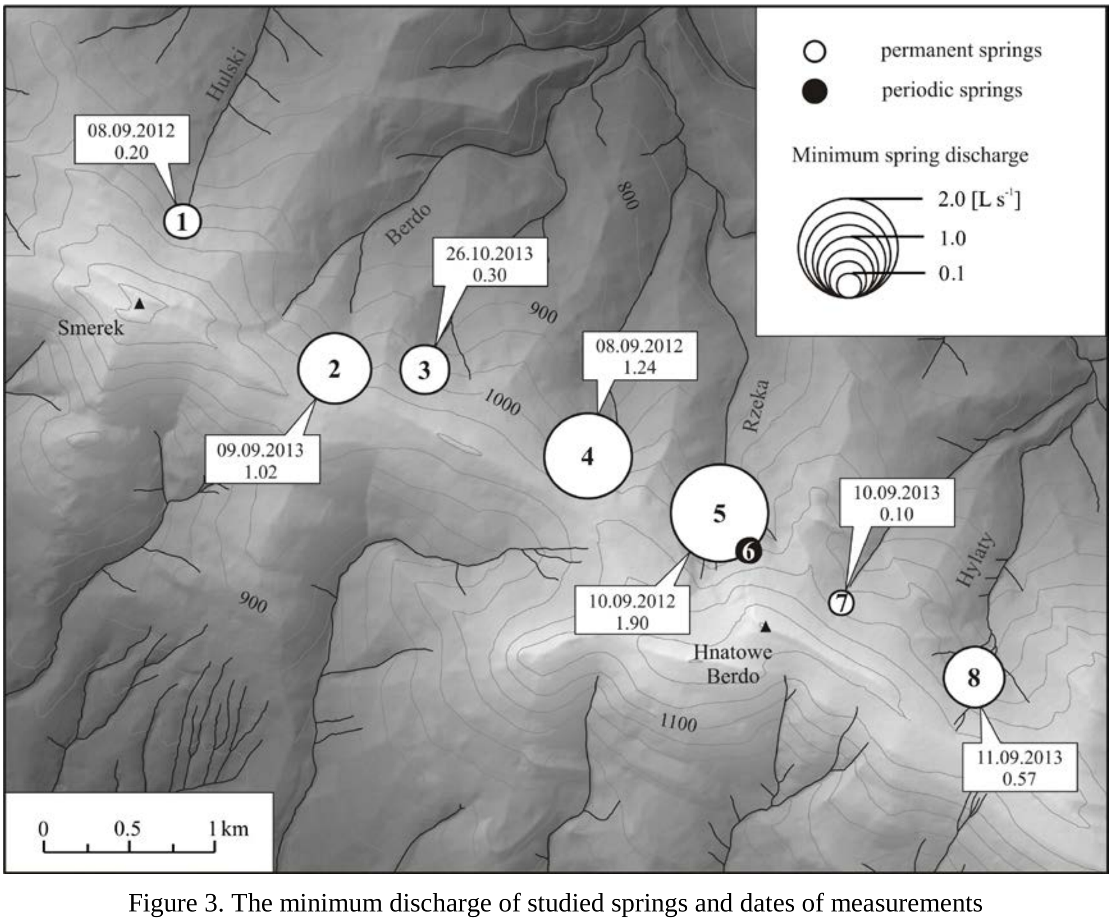

Figure 3. The minimum discharge of studied springs and dates of measurements

Half of the studied springs (4) produced more than 5Ls^{-1} on average. Spring No. 5 produced the highest average discharge, while Spring No. 6 produced the lowest (Table 2). Both springs, No. 5 and No. 6, are located in the Rzeka Stream catchment.

Minimum values in the study area range from 0.0 L s^{-1} for the periodic spring to nearly 2.0 L s^{-1} (Tab. 2). Aside from the periodic spring, the lowest measured discharge could be observed for Spring No. 7, which is found in the Hylaty Stream catchment (Fig. 3). On the other hand, the highest minimum discharge was noted for Spring No. 5 in the Rzeka Stream catchment (Fig. 3). It is important to note that the minimum discharge values listed in Figure 3 were measured during periods of strong drought in the autumn months of 2012 and 2013.

The highest measured discharge values for the eight studied springs exceed 5 L s^{-1}, reaching 19 L s^{-1} in the Rzeka Stream catchment (Table 2). Most maximum discharge values were measured in 2010 during a particularly wet period in the study area.

There exists a strong positive correlation between the discharge values for most of the studied springs (Table 3), which ranges from 0.77 to 0.97 ($\alpha \leq 0.05$). No statistically significant correlation was noted for springs No. 4 and No. 7.

The obtained discharge data suggest that two springs (No. 2, No. 4) may be classified as less variable, three springs may be classified as variable (No. 1, No. 5, No. 8), and two springs may be classified as highly variable (No. 3, No. 7). The spring characterized by the most variable discharge is Spring No. 7 (Table 2).

Table 2. Pearson correlation coefficient of selected spring discharge ($\alpha \leq 0.05$; * not significant)

Spring No.	2	3	4	5	7
2	1.00				
3	0.95	1.00			
4	0.84	0.77	1.00		
5	0.97	0.91	0.91	1.00	
7	0.90	0.96	0.66*	0.85	1.00

5. DISCUSSION

It is usually assumed that spring discharge in the flysch Carpathians normally does not exceed 0.5 L s^{-1}. The Bieszczady Mountains are characterized by even lower spring discharge values (Dobija, 1981; Dynowska & Pociask-Karteczka, 1999). According to Kleczkowski (1991), only about 4% of documented springs in the Eastern Beskidy Mountains yield more than one liter of water per second. Research has shown that the Polonina Wetlinska Massif has more high discharge springs – a total of 52 such springs – each producing more than one liter of water per second. A total of 879 springs were surveyed in the study area, found above 900 meters of elevation (Mocior et al., 2015).

It was also observed that all springs yielding more than 5Ls^{-1} are located on the northern slopes of Polonina Wetlinska (Mocior et al., 2015). Another research effort in the Hylaty Stream catchment – located on the northern slopes of Polonina Wetlinska – led to the documentation of 163 springs, of which four were found to yield more than one liter of water per second. Only two of these four springs produced more than 2Ls^{-1} of discharge (Bogusz, 2004): Spring No. 132 and Spring No. 151. The two springs identified by Bogusz (2004) most likely correspond to Spring No. 7 and Spring No. 8 identified in our research study (Tab. 1). Similar research was conducted by Żurek (2005) in the catchment of Głęboki Stream, which is also located on the northern slopes of Polonina Wetlinska. In this case, 9 out of 856 springs produced more than one liter of water per second. The majority of the studied springs in this case produced less than 0.1 L s^{-1}.

In addition, springs were surveyed in the Upper Wołosatka catchment, which is also located in the High Bieszczady Mountains, but outside of the study area discussed in this paper. In this second study area, only 3 out of 196 surveyed springs produced more than 1 Ls^{-1}. Most springs produced less than 0.1 Ls^{-1} (Rzonca et al., 2008). Research by Łajczak (1996) in the High Bieszczady Mountains showed the existence of 74 springs with discharge over 1 Ls^{-1}. In this case, the study area was large and covered four catchments: Terebowiec, Wołosatka, Rzeczyca, Dwernik. This was about 25% of the area of Bieszczady National Park. However, it is difficult to properly utilize these research results due to a lack of information on the hydrometeorological conditions present in the study area at the time.

High discharge springs are also quite rare in other parts of the flysch Carpathians in Poland. In the Tylicz area of the Low Beskidy Mountains (Magura geologic unit), only 4 out of 365 surveyed springs produced more than 3Ls^{-1} (maximum of 5Ls^{-1}). Most springs in this particular study area were in the range from 0.01 to 0.1 Ls^{-1} (Buczyński et al., 2007). Low discharge was also predominant in the Ryjak Stream catchment in Magura National Park, with 109 out of 120 surveyed springs producing discharge in the range from 0.01 to 0.1 Ls^{-1}. In this particular study, only one spring discharged over 1Ls^{-1} (Lasek, 2008). The long-term average discharge in the case of more than a dozen springs in the Magura flysch region in the Soła, Skawa, and Raba catchments was very low, ranging from 0.06 to 0.9 Ls^{-1} (Jokiel, 1997).

A comparison of the research results discussed in this paper and results published in the literature shows that certain local hydrogeological factors affect some springs in Polonina Wetlinska and result in high spring discharge, which is very rare in flysch areas of the Polish Carpathians. The springs analyzed in this study may be readily designated “high discharge” and the high concentration of such large springs on the northern slopes of Polonina Wetlinska may be readily called remarkable. In addition, the topographic catchments of these springs are quite small, ranging from 0.01 to 0.04 km^2 (Table 1), due to the very location of these springs close to the ridgeline of Polonina Wetlinska.

A strong positive correlation was determined for minimum and mean spring discharge and the surface area of spring topographic catchment areas (Fig. 4). Pearson linear correlation coefficient equals 0.79 in both cases and is statistically significant at $\alpha \leq 0.05$. However, there was no statistically significant correlation between maximum spring discharge and spring catchment surface area. High spring discharge is surprising in the context of a small catchment surface area. This may suggest spring recharge originating in areas located outside of each spring’s topographic catchment area. Such an additional recharge area would have to be large and would have to utilize a system of fractures and fissures following the ridgeline of the Polonina Wetlinska Massif.

One key characteristic of springs located in flysch areas is periodicity and discharge variances throughout the year, which is associated with the low retention capacity of bedrock in the area. The outcome of this is rapid spring response to atmospheric precipitation or the lack thereof (Waksmundzki, 1971; Dynowska, 1986; Łajczak, 1996; Małecka et al., 2007; Siwek et al., 2009). Measurements performed nearby by Polish National Hydrogeological Service in the hydrological years 2003–2013 have shown that the discharge of two observed springs (in Wetlina and in Dwerniczek) vary widely over the course of a year – up to three orders of magnitude (Kazimierski, 2004–2014).

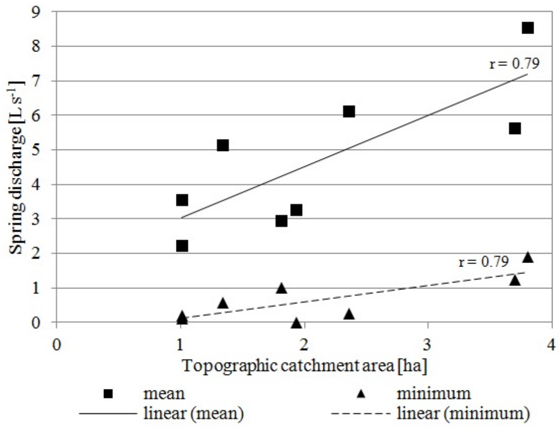

Figure 4. Mean and minimum spring discharge in relation to topographic catchment area

Research studies in other flysch regions in Polish Carpathians such as the headwaters of the Vistula River (Waksmundzki, 1971) and the northern slope of Babia Góra Mountain (Łajczak, 1981) also suggest that spring discharge varies substantially. Maillette’s index of variability ranged from 3.2 to several thousand for springs in the Vistula catchment and from 2.0 to 250.0 for springs on Babia Góra Mountain. Springs in the Polonina Wetlinska study area are also characterized by index of variability values from 5.0 to 101.7.

At the same time, the strong relationship between discharges for the studied springs is evidence of a similar recharge mechanism and a similar response time to rainfall recharge and snowmelt recharge.

It was also observed that water stages on the San River at the Zatwarnica gauge are strongly linked with spring discharge on the northern slopes of Polonina Wetlinska. Springs No. 2, 3, 5, and 7 are especially useful in that the largest numbers of discharge measurements are now available for them. The correlation between these four springs (discharge) and water stages on the San River at Zatwarnica is positive and also very strong. In these four cases, Pearson’s coefficient of linear correlation was 0.88, 0.99, 0.85, and 0.96, respectively, while the level of significance was $\alpha \leq 0.05$ (Fig. 5).

The minimum spring discharge documented during major droughts in the study area shows that seven out of eight of the large springs studied on the northern slopes of Polonina Wetlinska are permanent springs. Discharge variability indices make it possible to place the studied springs into

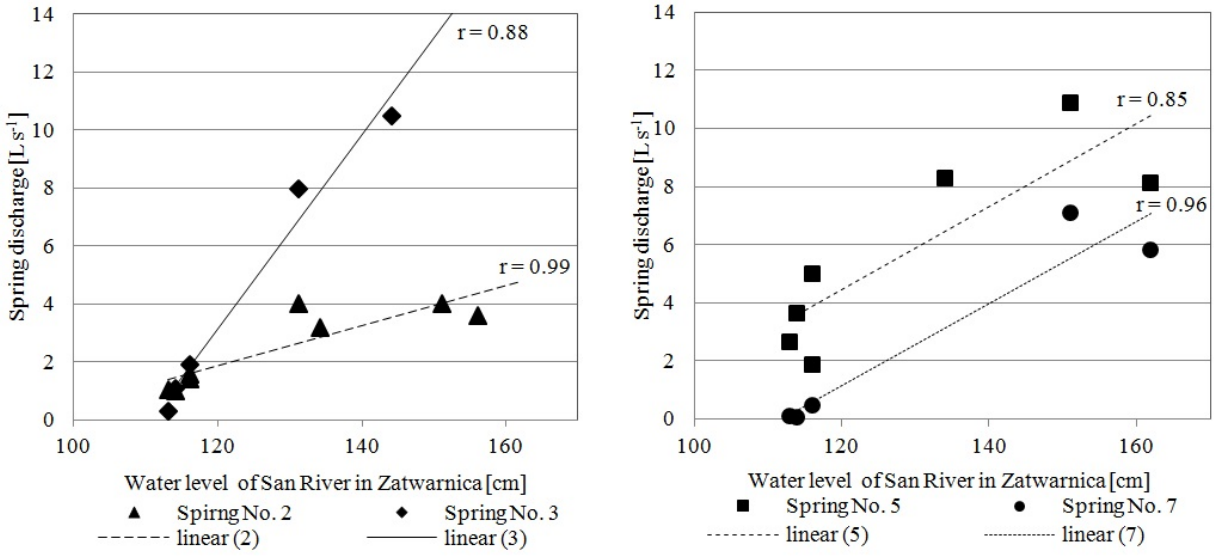

Figure 5. Spring discharge (springs No. 2, 3, 5 i 7) in the hydrological years 2012-2013 in relation to water stages for the Zatwarnica gauging site (San river)

classes from "stable" to "highly variable". Variances in spring discharge, some quite substantial, suggest that groundwater reservoirs recharging the springs are rather inconsequential. An indirect conclusion here is also that the distance between the studied springs and their recharge areas may be quite short.

At the same time, given the stable functioning of the studied springs as well as their high discharge and location at higher elevations, it is reasonable to state that spring discharge variances in this case are quite small and groundwater reservoirs are quite large. The supply of groundwater at higher elevations of Polonina Wetlinska is quite large based on the stable temperatures of spring water in the study area. The temperature of five springs was measured continuously in the period 2012–2014. The temperature of water in each studied spring did not vary more than 2°C during the year (Kisiel et al., 2015).

Research has shown that springs producing even more discharge are found below the timberline in areas covered with debris (Bogusz, 2004; Żurek, 2005; Rzonca et al., 2008). The presence of fewer, but more productive, springs on the northern slopes where the dip of the rock layers follows the dip of the slope and spring location is strongly linked with tectonic faults and fissures is a feature of the Polonina Wetlinska Massif above an elevation of 900 meters (Mocior et al., 2015). Hence, this further confirms the dependence of spring discharge on local tectonics in flysch areas (Rzonca et al., 2008).

The permanence of springs and their discharge are linked with flysch formation type associated with the location of a given spring. Krosno Beds with Otryt sandstone as well as Magura sandstone, Godula sandstone, Istebna sandstone, and Lgota sandstone facilitate the evolution of high discharge springs. In addition, the number and nature of fissures also do affect the supply of water in each type of formation (Kleczkowski, 1991; Chowaniec, 1998-1999). Finally, the small elevation difference (54 m) between six out of eight studied springs also helps confirm the dependence of spring location on structural characteristics.

6. CONCLUSIONS

The study confirmed the presence of eight very large, by flysch area standards, springs found high in the Polonina Wetlinska Massif. Seven out of eight are permanent springs. The discharge of these springs under favorable hydrometeorological conditions (wet periods) can reach 20 $L\,s^{-1}$. The studied springs are found amidst debris fields at upper elevations just below the upper tree line. The detection of discharge in seven of the studied springs during extreme drought lasting over extended periods of time makes it possible to establish that these are permanent springs. Some of the springs yield at least 1 $L\,s^{-1}$.

The topographic catchments of the studied springs are characterized by very small surface areas, which mean that spring recharge areas must be larger than topographic catchments. In addition, groundwater reservoirs must be relatively capacious, which makes it possible for a spring to yield large amounts of water on a continuous basis. In this case, the groundwater reservoir is a thick layer of Otryt sandstone following an NE dips, while the flow path of groundwater recharging the studied springs most likely follows the ridgeline of Polonina Wetlinska (the strike direction of rock layers). In addition, the flow path may be affected by the direction of faults and fissures, which are quite abundant in the study area. These geological features affect the capacity of groundwater reservoirs and their ability to yield water. While flysch reservoirs are not significant sources of groundwater, local structural characteristics (e.g. faults, fissures) may facilitate the occurrence of high discharge springs.

Acknowledgement

The paper was written as part of the research program „HydroBieszczady". The authors would like to thank all fieldwork participants.

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Received at: 08. 10. 2015
Revised at: 23. 12. 2015
Accepted for publication at: 01. 04.2016
Published online at: 04. 04. 2016