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HYDROGEOLOGICAL CHARACTERIZATION OF LOCAL GROUNDWATER RESERVOIRS IN THE KŁODZKO LAND (SUDETES - SW POLAND) BASED ON AN ANALYSIS OF THE DISCHARGES OF SPRINGS

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Abstract: The hydrogeological characteristics of the two types of local groundwater reservoirs found in the Kłodzko Land (Sudetes) have been made based on the analysis of the discharge of springs in Szczytna and Różanka. In the first of these spring discharge points, water flows out of Upper Cretaceous sandstones and mudstones. The other spring is associated with fractured and weathered mica schists and gneisses. The Różanka spring characterized by greater discharge variability than the fissured porous outflow in Szczytna. The latter one, due to the slower rate of water filtration in the rock medium, belongs to stable springs in terms of discharge. The local groundwater reservoir located in sedimentary rocks characterized by a much higher value of the groundwater volume stored (264,000 m^3) than the reservoir consisting of weathered and fractured crystalline rocks (1,918 m^3). In the case of the reservoir draining by Szczytna spring, the rate of groundwater exchange in the active zones is about 66 weeks. A distinctly shorter time (12 weeks) is necessary to exchange water in the fractured crystalline bedrock. The hydraulic conductivity for the aquifers in Szczytna and Różanka, calculated based on the recession coefficient, differ substantially from each other. They are 4.64 and 24.9 m/d, respectively.

Keywords: mountain areas, hydrogeological parameters, groundwater resources, spring

1. INTRODUCTION

A spring is a place where groundwater discharges onto the ground surface in a natural, spontaneous, and concentrated way. Groundwater outflows are a manifestation of groundwater circulation in the rock environment. Systematic and long-term observation of a spring's discharge enables the groundwater reservoir drained by such a spring to be characterized. The methodology used in crenological research for many years (Maillet, 1905; Wieczysty, 1982; Kowalski, 1984; Bonacci, 1993; Jokiel & Maksymiuk, 1995) allows calculation of many numerical characteristics describing, among others, the water storage capacity of reservoir rocks, the rate of exchange of water circulating in a reservoir, or the permeability of rocks in which groundwater accumulates. The applied computational methods are based on the assumption that the higher groundwater storage capacity, the slower groundwater resources are exhausted, which manifests itself in more stable and long-term supply of springs (Maillet, 1905; Kresic & Stevanovic, 2010; Buczyński & Rzonca, 2011).

Due to the occurrence of springs in great numbers, mountainous areas are most predisposed for hydrogeological characterization of local reservoirs using a spring discharge analysis. Hydrogeological studies designed to determine the resource characteristics of groundwater reservoirs have been conducted for many years in the Kłodzko Land area (Kowalski 1983; Kryza, 1983; Kryza & Tarka, 1992; Staśko & Tarka, 1996; Buczyński & Staśko, 2016). These studies primarily focused on reservoirs composed of crystalline rocks, such as gneisses, mica schists, and crystalline limestones.

Crystalline carbonate rocks were characterized by the best collector (storage) properties. A study on the Romanowo springs (karst springs in the Kłodzko Land area) carried out by Bocheńska et al., (2002) showed the values of the recession coefficient α of the discharge rate of the spring to be at a level of 10^{-3}, which gave the value of groundwater volume stored of 448,443 m^3. Based on the recession coefficients α, the residence time of karst water in the aquifer system was calculated and it was

115 days. Another study conducted in the Kłodzko Land area reveals that springs draining erlan formations (calcareous silicate rocks) are characterized by lower recession coefficients than gneiss springs and thus a higher groundwater volume stored of the reservoirs supplying these outflows. The higher groundwater volume stored of calcareous silicate rocks is confirmed by an analysis of the groundwater runoff modulus for small sub-catchments. For catchments located in the area of erlan lens, it is 10.7-18.0 $dm^3/s \cdot km^2$, whereas for catchments in the gneiss area 4.8-15.7 $dm^3/s \cdot km^2$ (Kryza & Tarka, 1992).

A study by Marszałek (1996) confirms the low storage capacity of low-lying gneiss groundwater reservoirs in the Sudetes. The calculated recession coefficients α were in the range of 0.0129 - 0.0159, corresponding to weathering fissure zones and the weathering cover, indicates fast depletion of groundwater resources. The groundwater volume stored in this zone drained by springs calculated based on the recession coefficients were within the range of 410 - 790 m^3. Compared to gneiss weathering covers, granite and hornfels weathering crust zones, frequently with a shallow zone of weathering fractures, are characterized by a slightly higher groundwater volume stored, ranging from 2,400 to about 6,000 m^3. In the case of strongly fractured subsurface quartz rocks, in turn, the groundwater volume stored values are in the range of 10,000-11,000 m^3. Relatively the highest values of the water storage capacity of low-lying groundwater reservoirs in crystalline rocks (except for crystalline limestones), with values of up to 22,000 m^3, are observed in the case of deeper zones of fissured granite and quartz rocks as well as well-permeable rock debris and rubble (Marszałek, 1996).

In turn, the resource characteristics of local groundwater reservoirs in sedimentary rocks of the Kłodzko Land based on the analysis of the discharge rate of springs has not been the subject of scientific papers. It should be known that the groundwater reservoirs in the study area have their origin in the geological structure, which is characterized by the occurrence of elevation and depression systems and tectonic fractures that divide them. From the point of view of groundwater accumulation, depressions perform a greater role since the groundwater flow is mainly concentrated in sedimentary rocks (Upper Cretaceous) that fill such depressions. On the other hand, elevations consisting of crystalline rocks, which account for about 50% of the study area, are evaluated very differently, predominantly as poorly hydrated areas (Malinowski, 1991).

The aim of this article is to deepen the knowledge regarding the resource capacity and hydrogeological characteristics of local groundwater reservoirs, not only located in the active exchange zone in crystalline rocks, but also at places where diagenized sedimentary rocks occur, which are one of the main groundwater collectors in the Kłodzko Land.

2. STUDY AREA

The hydrogeological characterization of local groundwater reservoirs was performed based on the analysis of the discharges of two springs in Szczytna and Różanka observed on a continuous basis (Figure 1). Both these localities are situated in the Kłodzko Land area in the Sudetes in south-western Poland. The springs analyzed are covered by the network of groundwater monitoring conducted by the National Hydrogeological Service. The spring in Szczytna has been monitored since 1987, whereas the outflow in Różanka since 1990.

The Szczytna spring is an ascending spring of fissured-layered type and it is located at an elevation of 478 m a.s.l., at the foothills of the Stołowe Mountains (Figure 1). Water flows out of Upper Cretaceous sandstones and mudstones in the contact zone between these rocks (Figure 2). The spring is situated on a gentle slope of the Kamienny Potok and Czerwona Wody valley. It is the zone of an erosion cut in the valley formed in mudstone that is exposed on the left slope of the Czerwona Woda stream, which is a tributary of the Kamienny Potok River. Upper Cretaceous sedimentary rocks, belonging to the geological unit named the Intra - Sudetic Basin, occur in the bedrock in the spring area. Apart from sandstones and mudstones, this unit is also consists of marls with conglomerate interbeds. These rocks were formed about 95 – 75 million years ago, in a shallow warm sea among islands composed of crystalline rocks of the Paleozoic era (Stupnicka, 2013).

In terms of hydrogeological conditions, in fractured Upper Cretaceous formations two aquifer levels are distinguished, the upper one and the lower one, divided by a complex of poorly permeable sediments. In tectonically engaged areas, these levels remain in hydraulic contact (Figure 2). Waters of the Cretaceous level are pressurized waters, locally sub-artesian, very rarely locally also with an unconfined water table. The depth to the aquifer layer is from several meters to 300 m. The aquifer thickness is variable, on average 60-80 m in the upper level and 30-50 m in the lower level. These levels are characterized by varying hydrogeological parameters, which are dependent on the tectonic engagement of the area. The greater it is, the more favorable the conditions are (Kowalski, 1983).

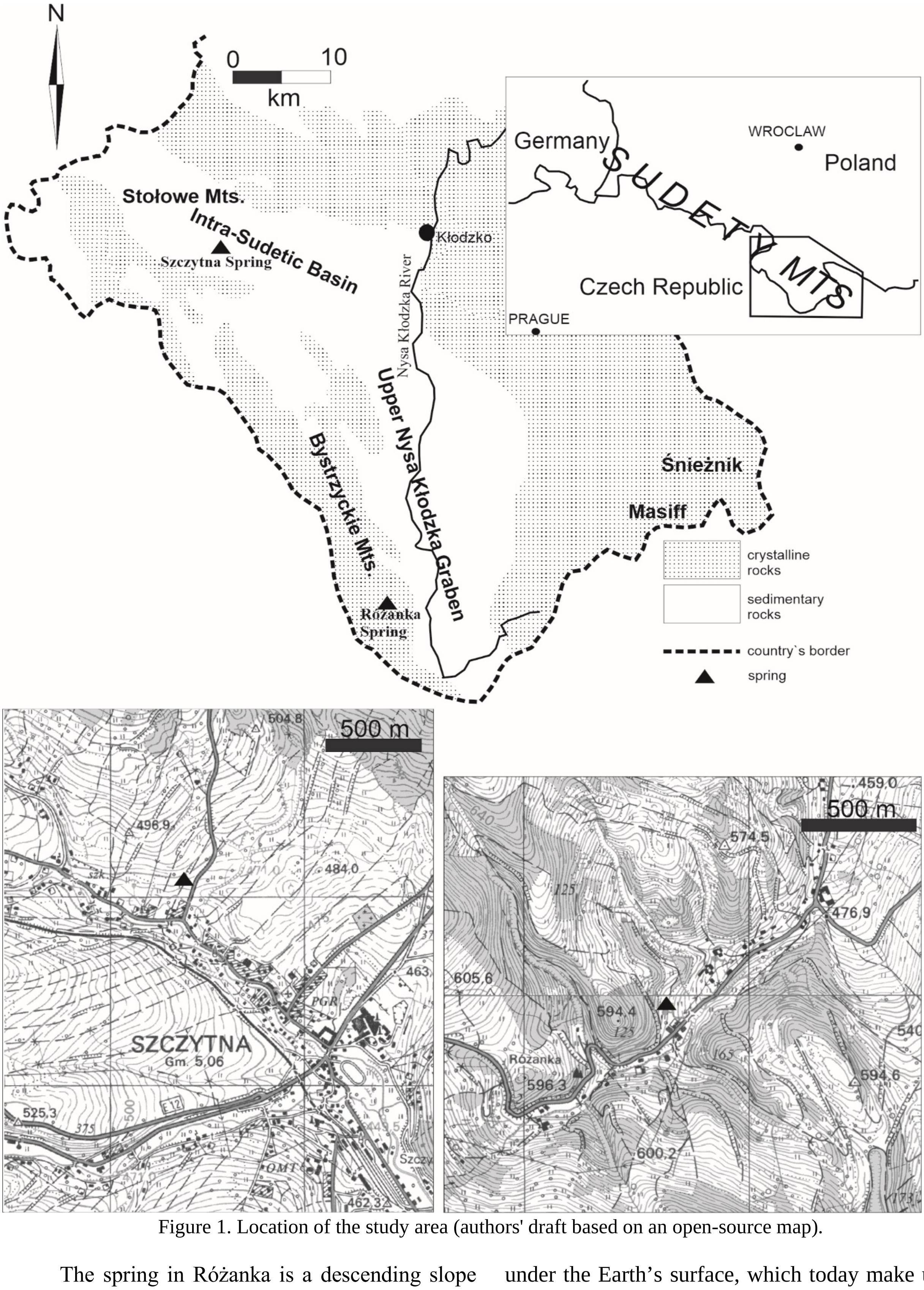

Figure 1. Location of the study area (authors' draft based on an open-source map).

The spring in Różanka is a descending slope spring that is located at an altitude of 522 m a.s.l. in the southern part of the Bystrzyckie Mountains, being part of the geological structure of the Bystrzyca-Orlice metamorphic area. It is a unit consisting of metamorphic crystalline rocks that developed deep under the Earth's surface, which today make up the highly elevated mountain frameworks. Early Paleozoic rocks that underwent deformation during the Variscan movements 380–340 million years ago occur in the bedrock. Gneisses and mica schists with interbeds of amphibolites, erlans, marbles, quartzites, and graphite-quartz slates are the main rocks composing the bedrock (Stupnicka, 2013).

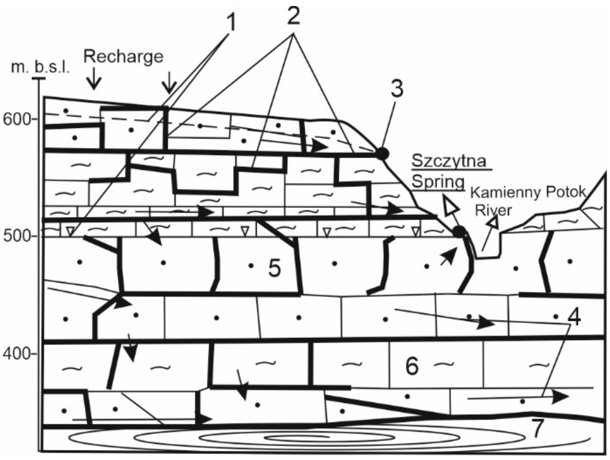

Figure 2. Schematic diagram of recharge of the spring zones of the upper and lower aquifer horizons in the Szczytna spring area (according to Kowalski, 1983).
1- groundwater table, 2- water-bearing fracture network, 3- springs, 4- groundwater flow directions, 5- sandstones, 6- mudstones, 7- mica schist

In hydrogeological terms, the Różanka spring is associated with fractured and weathered metamorphic rocks of the older Paleozoic (predominantly gneisses and mica schists with erlan and crystalline limestone lens). Two aquifer zones with usable water are distinguished. The upper zone occurs in the subsurface weathered part of the rocks, with an unconfined or slightly confined water table, without natural isolation, and hydraulically communicated with the lower situated strongly fractured/fissured aquifer (Figure 3). This zone extends to a depth of about 40 m. The other zone, in turn, called the lower zone, is associated with deeper water circulation in the system of fractures and fissures in tectonic loosening areas in crystalline rocks, with a confined water table (a depth of up to 150 m). The thickness of aquifer zone varies and reaches up to 40 m (Figure 3).

3. METHODOLOGY

Unlike a single discharge measurement, only long-term and systematic observations of a spring's discharges allow its water regime to be identified. As of 2021, five springs in the Kłodzko Land were covered by continuous discharge measurements as part of the national groundwater monitoring system, including four springs associated with Mesozoic sedimentary formations and one spring discharge point associated with Paleozoic crystalline rocks.

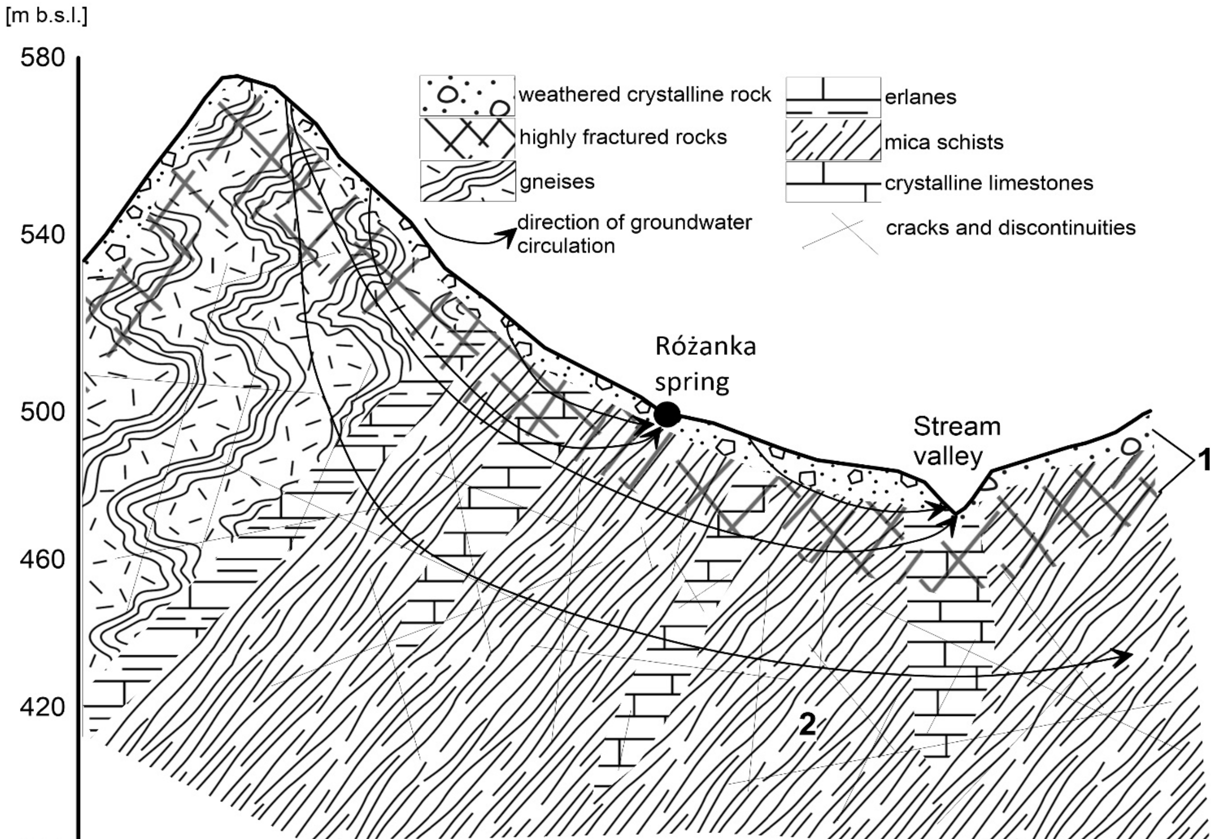

Figure 3. Schematic diagram of groundwater circulation in the active exchange zone in crystalline rocks of the study area. 1- upper zone of groundwater circulation 2 - lower zone of groundwater circulation

Discharge measurements of the springs in Szczytna and Różanka are continuous, and they are made once a week by the National Hydrogeological Service. The 2014-2021 period was selected for the analysis due to its undisturbed measurement continuity and the absence of gaps in the data. The other three spring discharge points had too long time interruptions in the data as well as the data were fragmented and inhomogeneous.

In the case of the springs monitored by the National Hydrogeological Service, automated systems for monitoring water flowing out are employed by using a V-notch weir equipped with a water level recorder. In such case, the discharge rate is calculated based on the rating curve equation.

Spring discharge is the most important feature of an outflow and forms the basis for further calculations of hydrogeological characteristics. During the first stage of this research, maximum discharge (Q_{max}) and minimum discharge (Q_{min}) values as well as the means were calculated as the arithmetic mean and the median (Q_{mean} and Q_{median}) based on the 2014-2021 hydrological data. Three coefficients of variation were also calculated for the spring discharge according to Pearson, Maillet (1905) and Meinzer (1923) (formulas 1, 2, and 3, respectively).

Pearson's coefficient of variation:

$$C_v = \frac{Os_x}{M_x} \qquad [1]$$

C_v – Pearson's coefficient of variation;
Os_x –standard deviation of the variable x;
M_x – arithmetic mean of the variable x.

The lower the value of the coefficient of variation C_v, the lower the dispersion of the examined feature. Due to the relativity of this measure, the obtained results can also be given in percent. With C_v values lower than 20%, the variability of a given feature is considered to be low, 20% – 40% moderate, 40%–100% high, 100 % – 150 % very high, while above 150% extremely high. It is commonly accepted that with a coefficient of variation lower than 10%, the examined empirical distribution shows insignificant differences (Zeliaś, 2000).

The coefficient of variation of the spring discharge according to Maillet (1905):

$$C_{Ma} = \frac{Q_{max}}{Q_{min}} \qquad [2]$$

C_{Ma} – coefficient of variation of the spring discharge according to Maillet;
Q_{max} – maximum spring discharge over the study period [dm^3/s];
Q_{min} – minimum spring discharge over the study period [dm^3/s].

The coefficients derived for individual outflows allow them to be classified in the group of constant springs if $1 < C_{Ma} < 2$, slightly variable: $2 < C_{Ma} < 10$, variable: $10 < C_{Ma} < 50$, and very variable at $C_{Ma} > 50$ (Wieczysty, 1982).

The coefficient of variation of the spring discharge according to Meinzer (1923):

$$C_{Mn} = \frac{Q_{max} - Q_{min}}{Q_{mean}} \qquad [3]$$

C_{Mn} – coefficient of variation of the spring discharge according to Meinzer;
Q_{max} – maximum spring discharge over the study period [dm^3/s];
Q_{min} – minimum spring discharge over the study period [dm^3/s];
Q_{mean} – mean spring discharge over the study period [dm^3/s].

Based on this coefficient, constant springs can be distinguished where $0 < C_{Mn} < 25\%$, slightly variable $25\% < C_{Mn} < 100\%$, and variable where $C_{Mn} > 100\%$ (Křiž, 1973; Kresic & Stefanovic, 2009).

During the next stage, an attempt was made to determine the seasonal variability of the springs' discharges based on the seasonality measures according to Markham (1970). The effect was the calculation of seasonality indices (IsQ) for the two outflows studied. This method assumes that the value of the analyzed variable in a given month is represented by a vector (r_{Si}) with its length proportional to the value of this variable and its angle of inclination (α_{Si}) (formula 4) dependent on the location of the middle of a given month relative to the beginning of the hydrological year.

$$\alpha_{Si} = \frac{360 \cdot L_S}{365} \qquad [4]$$

α_{Si} – angle of inclination of the vector r_{Si} for monthly (or daily) values;

L_S – number of days between the beginning of the hydrological year and the middle of a given month or a specific day.

As a result of application of this procedure with respect to monthly values, 12 vectors are created for which the resultant vector R_S can be determined, with the modulus $|R_S|$ and the direction ω. By dividing the length of the modulus of the resultant vector $|R|$ by the total length of the moduli of the partial vectors $|r_{si}|$, we derive the seasonality index IsQ (formula 5):

$$IsQ = \frac{|R_S|}{\sum_{i=1}^{365} |r_{si}|} \cdot 100\% \quad [5]$$

IsQ – seasonality index;
R_s – length of the resultant vector of the vectors r_{si};
r_{si} – vector corresponding to the mean value of the feature in the *i*-th month of the hydrological year.

The seasonality index assumes values in the 0–100% range and the degree of seasonality of the examined feature increases with its increase.

The next important stage of this study was to determine regression curves for the springs, which allow the storage capacity of the groundwater reservoir drained by the respective spring to be analyzed. The recession curves illustrate the rate of spring discharge recession (depletion of groundwater resources) during a rainless period. A rainless period is considered to be a period during which no effective precipitation occurred which would interrupt the recession of the discharge (Wieczysty, 1982). Therefore, the recession curve is a picture showing the relationship between a spring's discharge rate and the degree of filling of the groundwater reservoir drained by this outflow. The structure of recession curves is based on identification and analysis of several-week-long periods with a decreasing discharge.

After selecting minimum four-week-long sections of the discharge recession, the recession coefficients α in a rainless period were determined by applying the logarithm to the Maillet equation (formula 6):

$$Q_t = Q_o e^{-\alpha t} \quad [6]$$

Q_t – spring discharge intensity after time t [m^3/s];
Q_0 – initial spring discharge intensity [m^3/s];
t – recession period;
α – recession coefficient of the spring discharge.

The recession coefficient (formula 7) was calculated by converting the Maillet formula and deriving the following formula:

$$\alpha = \frac{lnQ_0 - lnQ_t}{t} \quad [7]$$

The recession coefficient α is a dimensionless value directly proportional to the rate of recession and decrease of water resources. This means that the higher the value of the coefficient is, the greater the inclination of the recession curve and the faster rate of depletion of resources. Knowledge of the values of the recession coefficient α allows us to estimate for any spring discharge the amount of water accumulated in the groundwater reservoir, i.e. the groundwater volume stored W (formula 8]. For both springs, the mean groundwater volume stored W_{mean} were determined using the long-term average discharges:

$$W_{mean} = \frac{86400 \cdot Q_{mean}}{\alpha} \quad [8]$$

W_{mean} – mean groundwater volume stored [m^3];
Q_{mean} – mean spring discharge [m^3/s];
α – recession coefficient.

In the next step, the rate of groundwater exchange in the active exchange zone was calculated using the renewal coefficient η (formula 9) (Tomalski & Tomaszewski, 2015).

$$\eta = \frac{VZR}{W_{mean}} \quad [9]$$

η – renewal coefficient;
VZR – mean annual total discharge of spring water [m^3].

This coefficient reveals how many times a year the mean groundwater volume stored is exchanged or how long this exchange lasts.

During the last stage of these calculations, the mean hydraulic conductivities k (formula 11) of the rocks accumulating and transmitting groundwater, drained by the described springs, as well as the groundwater flow time from the watershed to the outflow point τ were determined (formula 12).

An experiment conducted by Kowalski (1984) demonstrates that, according to the Dupuit equation, the hydraulic gradient does not affect a change in the recession coefficient α, but it determines the value of the discharge itself. Therefore, a change in the thickness of the saturated zone and in the groundwater flow path length does not result in a change in the recession rate of spring discharge (α is constant). Moreover, there are grounds for claiming that the recession coefficient is significantly correlated to hydraulic conductivity (r > 0.9). This relationship is described by formula 10:

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

When we convert the above formula, we obtain the following:

$$k = \frac{\alpha}{0.000469} \quad [11]$$

k – hydraulic conductivity [m/d];
r – correlation coefficient.

In turn, to determine the groundwater flow time from the watershed to the outflow point τ, the below formula was applied (Jokiel & Maksymiumk, 1995):

$$\tau = 2 \cdot \alpha^{-1} \quad [12]$$

τ - water flow time in days.

The above characteristic should be treated as an element of assessment of the rate of groundwater renewal in a reservoir and it is similar to the characteristic that the renewal coefficient η is.

4. RESULTS AND DISCUSSION

The long-term crenological research conducted in mountainous areas of the Kłodzko Land (Buczyński et al., 2011) demonstrates that outflows with the discharge rate not exceeding 1 dm^3/s, with a median equal to 0.27 dm^3/s, are predominant. The Różanka spring, draining weathered zones of Paleozoic crystalline rocks represented by mica schists and gneisses, which predominate in mountainous areas of the Kłodzko Land, fits this range of values. On the other hand, the spring in Szczytna with discharges above 5 dm^3/s, draining Upper Cretaceous sedimentary rocks, belongs to more efficient groundwater outflows in the Kłodzko Land. Higher discharges (several dozen dm^3/s) in mountainous areas of the Kłodzko Land can only be found where crystalline carbonate rocks occur. An example can be the vauclusian springs in the Kleśnica River valley (Śnieżnik Massif) with their maximum discharges reaching 100 dm^3/s (Ciężkowski, 1989; Olichwer & Otrębski, 2016) or the "Romanów springs" with a discharge rate of more than 25 dm^3/s, draining limestones and crystalline dolomites (Bocheńska et al., 2002).

According to Meinzer's division (1923), the outflow in Szczytna with discharges ranging from 5 to 8.57 dm^3/s (Figure 4) is classified in discharge class V (1-10 dm^3/s). In turn, the Różanka spring with discharges from 0.11 to 0.59 dm^3/s (Figure 5) is classified in class VI (0.1-1 dm^3/s). More detailed characteristics of the described outflows, based on the data from the hydrological years 2014-21, are contained in Table 1.

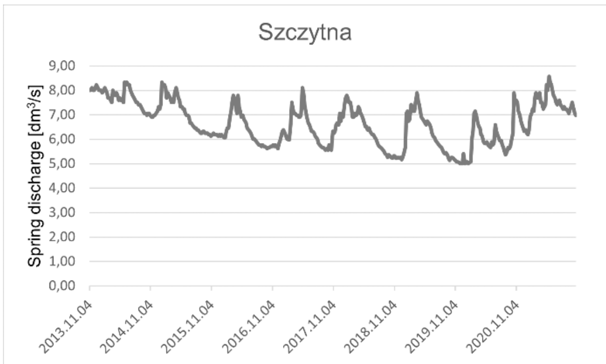

Figure 4. Variability of the Szczytna spring discharge over the 2014-2021 period.

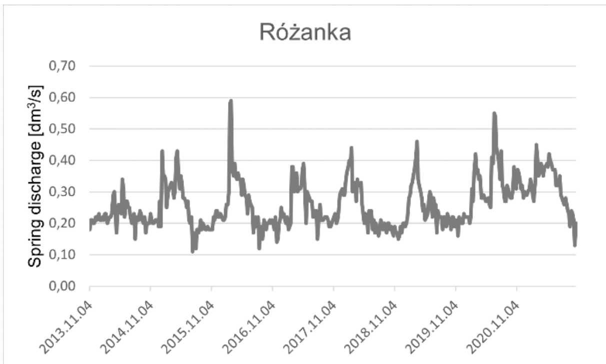

Figure 5. Variability of the Różanka spring discharge over the 2014-2021 period.

Table 1. Characteristics of discharges of the springs in question in the hydrological years 2014-2021.

Characteristics	Szczytna Spring	Różanka Spring
Q_{max} [dm^3/s]	8.57	0.59
$Q_{mean/mediana}$ [dm^3/s]	6.66/6.67	0.26/0.23
Q_{min} [dm^3/s]	5.0	0.11
Q_{cv} [%]	13.3	29.2
C_{Ma} [-]	1.71	5.36
C_{Mn} [%]	53.6	184.6

Q_{max}, Q_{mean}, Q_{min} - maximum, average, minimum discharge; Q_{cv} - pearson's coefficient of variation; C_{ma} - coefficient of variation of the spring discharge according to Maillet; C_{mn} - coefficient of variation of the spring discharge according to Meinzer

Changes in spring discharge can be assessed using Pearson's standard coefficient of variation (Q_{cv}). In the case of the Szczytna spring with a percentage value of 13.3 %, the variability of its discharge can be considered as low (<20 %). As regards the Różanka outflow, on the other hand, the level of its discharge variability (29.2 %) is moderate (20-40 %). Two more parameters characterizing the discharge variability are frequently used in the hydrogeological literature. These indicators were first proposed by Maillet (1905), while slightly later by Meinzer (1923). According to Maillet's classification (C_{Ma}), the Szczytna spring is a constant outflow ($1< C_{Ma}< 2$), whereas the Różanka outflow is a slightly variable spring ($2<C_{Ma} < 10$). According to the criteria adopted by Meinzer, in turn, the Szczytna spring is slightly variable ($25\% < C_{Mn}< 100\%$), while the spring in Różanka is variable ($C_{Mn} > 100\%$).

The long-term mean discharges of the described springs for the 2014-2021 period are respectively 6.66 dm^3/s for the Szczytna outflow and 0.26 dm^3/s for the Różanka outflow. In the case of variable discharge springs, the median is a better measure to describe the mean discharge because it is less sensitive to extreme discharges; in the case of the spring discharge point in Różanka, it is 0.23 dm^3/s, being lower than the value of the arithmetic mean (Table 1).

When analyzing the seasonal spring discharge variability, it can be seen that a higher percentage of the annual total runs off during the cold half of the year (November XI- April IV), respectively 53 and 57.7 % (Table 2).

Table 2. Seasonal characteristics of the springs' discharges in the hydrological years 2014–2021.

Spring	Year		Cold half of the year XI-IV		Warm half of the year V-X		IsQ
	Q_{mean}	[%]	Q_{mean}	[%]	Q_{mean}	[%]	[%]
Szczytna	6.66	100	6.86	53	6.46	47	1.54
Różanka	0.26	100	0.28	57.7	0.24	42.3	9.63

Q_{mean} - average discharge [dm^3/s]; IsQ - seasonality index

Taking into account the mean monthly discharges from the analyzed long-term period, the highest discharge rates were recorded at both points in March (Figures 6 and 7), 7.38 dm^3/s in Szczytna and 0.31 dm^3/s in Różanka. On the other hand, the least efficient months proved to be September (6.04 dm^3/s) in the case of the Szczytna spring (Figure 6) and October (0.21 dm^3/s) in the case of the Różanka spring (Figure 7).

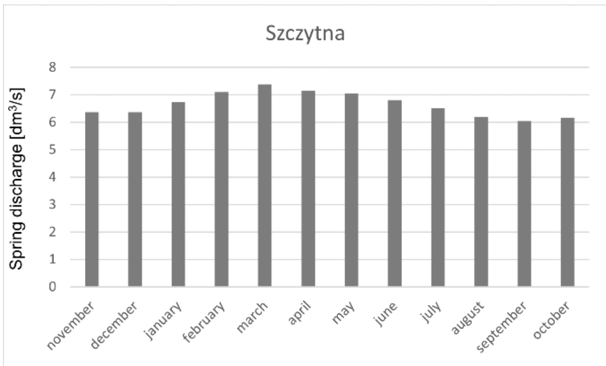

Figure 6. Mean monthly discharges of the Szczytna spring for the long-term period 2014-2021.

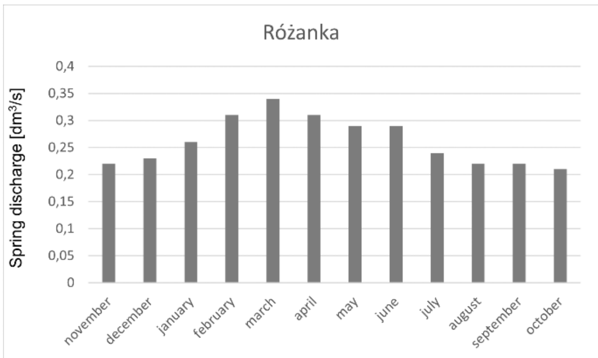

Figure 7. Mean monthly discharges of the Różanka spring for the long-term period 2014-2021.

The analysis of the seasonal discharge variability was performed based on the seasonality measures according to Markham (1970). The calculated seasonality indices (IsQ) are low, in particular in the case of the Szczytna spring (1.54 %). A slightly higher value of Is= 9.63 % (Table 2) was calculated for the spring discharge point in Różanka. The low values of Is, such as those for the Szczytna outflow, are characteristic of springs whose groundwater reservoirs slowly transmit their resources, thus causing the outflow from the spring to be relatively evenly distributed. The lowest values of Is are typical for large porous springs, whereas values above 20 % are typical for karstic and fissured springs (Moniewski, 2015; Bartnik & Moniewski, 2019). As a reminder, the Szczytna outflow is porous-fissured (dense and fractured sedimentary rocks), whereas the Różanka spring is fissured (crystalline rocks).

To perform a thorough analysis of the storage capacity of the groundwater reservoir drained by a specific spring, the so-called recession curves were determined. From the discharge observation period over the hydrological years 2014-21, at least over a dozen four-week long discharge recession sections were selected (Figures 8, 9). The longest discharge recession for the Szczytna spring lasted 203 days (29 weeks, from April 2, 2018 to October 22, 2018), while for the Różanka spring 56 days (8 weeks, from May 17, 2021 to July 12, 2021).

The obtained mean recession coefficients α reach values of about 0.002 for the Szczytna spring and 0.01 for the Różanka outflow (Table 3). The derived α values suggest much faster depletion of groundwater resources in the case of the reservoir drained by the Różanka outflow. The Szczytna

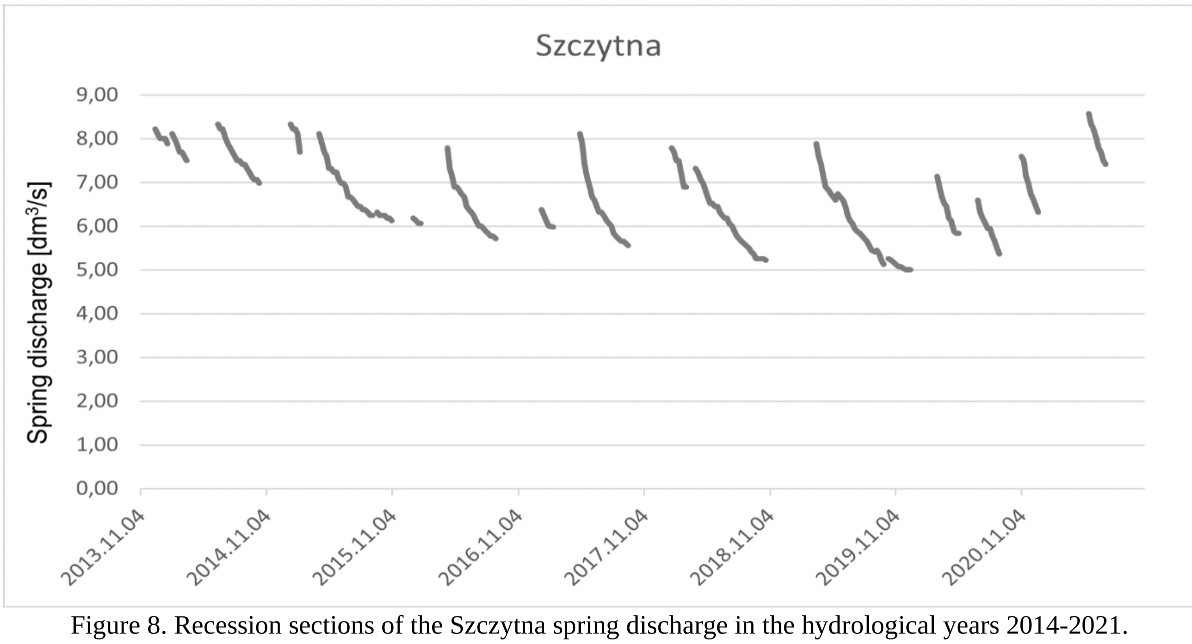

Figure 8. Recession sections of the Szczytna spring discharge in the hydrological years 2014-2021.

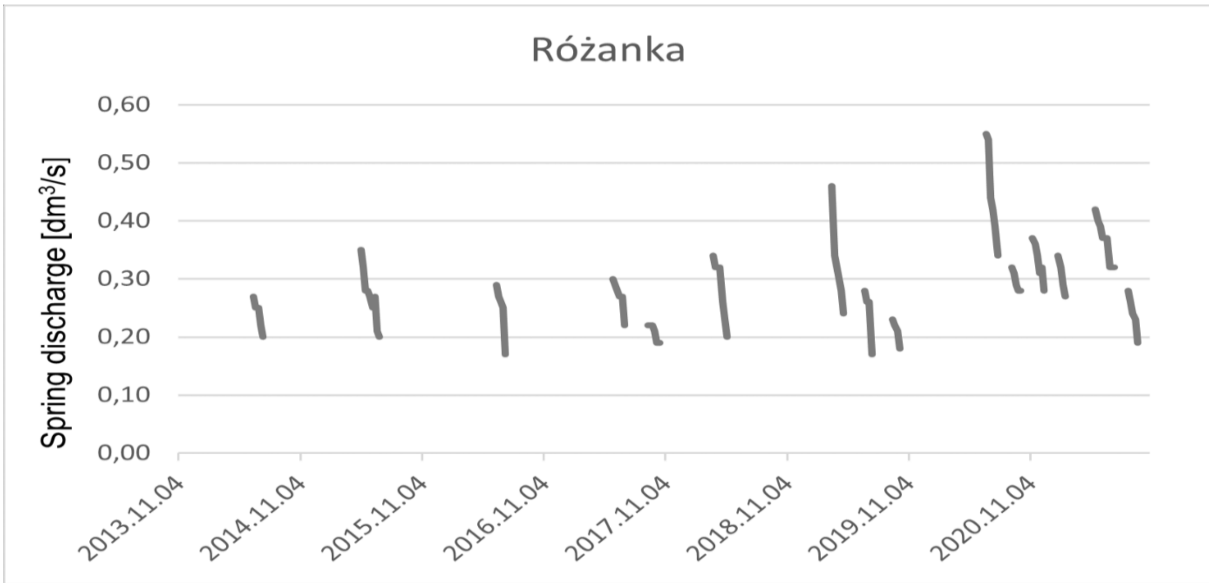

Figure 9. Recession sections of the Różanka spring discharge in the hydrological years 2014-2021.

Table 3. Characteristics resulting from the analysis of the springs' discharge recession.

Spring	α_{mean}	α_{max}	W_{mean} (m^3)	W_{max} (m^3)	η	52/η	k [m/d]	τ [d]
Szczytna	0.002177	0.003737	264,319	340,123	0.79	66	4.64	918
Różanka	0.011710	0.023761	1,918	4,353	4.27	12.2	24.9	170

α_{mean}, α_{max} – average and maximum recession coefficient; W_{mean}, W_{max} – average and maximum groundwater volume stored; η – renewal coefficient [1/year]; 52/ η – renewal coefficient in weeks, k – hydraulic conductivity, τ- groundwater flow time from the watershed to the outflow point in days

spring, draining the reservoir composed of fractured mudstones and sandstones, is characterized by a lower recession coefficient (Table 3). The groundwater reservoir supplying the Szczytna outflow is much more stable and abundant than the reservoir drained by the Różanka spring which consists of fractured crystalline rocks. The greater stability of the Szczytna outflow's discharge is due to the fact that the groundwater reservoir is recharged with waters from a deeper circulation system which is a transitional system between the local one and the regional one (several hundred meters deep). The amount of water accumulated in this reservoir is confirmation that Cretaceous groundwater reservoirs are much more abundant compared to Paleozoic ones. Knowing the recession coefficient for any spring discharge, the amount of water accumulated in the underground reservoir can be estimated. Given the mean discharges of the springs, the average groundwater volumes stored of their reservoirs were 264,319 m^3 for the Szczytna spring and only 1,918 m^3 for the Różanka spring (Table 3). Significant differences in the storage capacities of these different groundwater reservoirs can be seen, the difference being almost 140 times.

The analysis of the values of the renewal coefficient η provides interesting information. In the case of the reservoir consisting of fractured Cretaceous sandstones and mudstones, the rate of groundwater exchange in the active zones is about 66 weeks (462 days) (Table 3). This means that once per 1.3 year the entire volume of water in the reservoir is exchanged. A distinctly shorter time (12 weeks) is necessary to exchange water in the fractured crystalline bedrock since the entire volume of water is fully exchanged once a quarter. The values shown in Table 3 are evidence that the reservoir in Różanka is a low-lying reservoir recharged with waters originating from a local shallow groundwater circulation system that formed in weathered and strongly fractured crystalline rocks.

The recession coefficients were also the basis for determining the hydraulic conductivity "k" for the individual aquifer zones. The hydraulic conductivity for the aquifers in Szczytna and Różanka, calculated based on the recession coefficient, differ substantially from each other. They are 4.64 and 24.9 m/d, respectively (Table 3). The averaged k value of the groundwater reservoir drained by the Szczytna spring fits the k values obtained using other research methods. This is confirmed by the studies conducted by Tarka (2006). To characterize the water-bearing capacity of Cretaceous formations in the Sudetes, the hydraulic conductivity was calculated based on pumping tests. For the entire set of the analyzed boreholes, the hydraulic conductivity values were within the range from 0.02 to 167.04 m/d, while the mean geometric value of the hydraulic conductivity was 2.49 m/d. Almost half (46.5%) of the k values were lower than 2.5 m/d, whereas the vast majority of them was in the range of up to 10 m/d.

The hydraulic conductivity of the aquifer drained by the Różanka spring standing at 24.9 m/d (Table 3) is quite high for the weathered and fractured bedrock of metamorphic rocks in the study area. The k values ranging between 0.2 are 12 m/d are predominant in the literature (Kryza, 1983; Kryza & Kryza, 1983; Marszałek et al., 2011). The k values above 20 m/d in the Sudetes area are rather typical for well-permeable rock debris and weathered granite rocks (Marszałek, 1996). The significant permeability of the reservoir rocks in the Różanka spring area can be explained by strong weathering fractures in the crystalline rocks and the high water carrying capacity of fissures and fractures. Thus, the Różanka spring is rather supplied from the fractured/fissured aquifer than from the weathering crusts of metamorphic rocks that cover this aquifer. In the Kłodzko Land area, such crusts are rather classified as poorly permeable sediments with a hydraulic conductivity not exceeding 1 m/d (Olichwer et al., 2021).

Worth noting are also the large differences in the groundwater flow time from the watershed to the outflow point τ in the reservoirs considered. For the aquifer in Szczytna, the theoretical water flow time is long, notably 918 days (Table 3). For the zone in Różanka, the parameter τ is lower and it is 170 days (Table 3). This latter value is close to the time over which water remains in the environment of karstified and fractured crystalline limestones of the Kłodzko Land (Bocheńska et al., 2002). Taking additionally into account the filtration parameters (hydraulic conductivity k) of the rock environment, this means that the distance covered by water both in the sedimentary rock reservoir and in the fractured crystalline rock reservoir is very similar, about 4300 m. This value should not be equated to the distance of the recharge areas from the described springs since groundwater circulation pathways are related to the bedrock fracture system. This particularly applies to the reservoir drained by the spring in Szczytna where the circulation is deeper and the outflow is ascending.

The described characteristics prove that water resources of the local Cretaceous sedimentary reservoir are poorly renewable with a relatively large amount of accumulated water. Resources accumulated in the reservoir in the fractured crystalline bedrock are characterized by a much faster renewal rate. The reservoir drained by the Różanka spring is characterized by a small water storage capacity and a relatively fast groundwater flow. The water flow time is several months here. Therefore, theoretically, these resources can be renewed several times during a year. These evidences the high water carrying capacity of fissures and fractures occurring in the reservoir.

5. CONCLUSIONS

In the Kłodzko Land area, three main types of local groundwater reservoirs can be distinguished where Paleozoic crystalline rocks and Cretaceous sedimentary rocks occur. The first one is associated with the bedrock consisting of fractured sandstones, mudstones, and marls (Cretaceous rocks). The second one is linked to the weathered and fractured bedrock of crystalline rocks, predominantly represented by Paleozoic gneisses and mica schists. The third type includes fractured, karstified Paleozoic crystalline limestones and erlans forming lens and interbeds in the gneiss and mica matrix.

The hydrogeological characteristics of the first two types of groundwater reservoirs found in the Kłodzko Land have been made in this article based on the analysis of the discharge rates of two continuously observed springs in Szczytna and Różanka. In the first of these spring discharge points, which is an ascending spring, water flows out of Upper Cretaceous sandstones and mudstones in the contact zone between these rocks. The other spring is associated with fractured and weathered mica schists and older Paleozoic gneisses.

The Różanka spring, whose supply is determined by the degree of weathering-induced fractures of the crystalline aquifer, is small and characterized by greater discharge variability than the fissured porous outflow in Szczytna. The latter one, due to the slower rate of water filtration in the rock medium, belongs to stable springs in terms of discharge.

The conducted analysis of the springs' discharges and the determined recession coefficients have allowed us to evaluate the rate of depletion of the groundwater reservoirs and their groundwater volume stored. The local groundwater reservoir located in diagenized sedimentary rocks of the Cretaceous era is characterized by a lower recession coefficient and a much higher value of the groundwater volume stored than the reservoir consisting of weathered and fractured crystalline rocks.

The average values of the recession coefficient for the Szczytna outflow at a level of 10^{-3} inform about a lower rate of depletion of groundwater resources in this reservoir compared to the reservoir drained by the Różanka spring. The limited thickness of the active water exchange zone and the much shallower groundwater circulation, than in the case of Cretaceous rocks, contribute to the small water storage capacity of this reservoir located in the fractured and weather crystalline rock mass. The groundwater volumes stored at a level of several thousand m^3 of shallow reservoirs formed on solid crystalline rocks, in conjunction with the occurrence of long dry periods during the summer and autumn period, may cause periodic problems with supply of water to the population. In the Kłodzko Land, single households or small human settlements use spring intakes or drainage intakes located in the weathered crystalline bedrock zone.

The only groundwater reservoirs in crystalline rocks that can compete with Cretaceous reservoirs in terms of groundwater volume stored are groundwater reservoirs that occur in lens of fractured and karstified crystalline limestones and erlans. Karst reservoirs are marked by deeper circulation than other crystalline rocks surrounding them as well as by a higher water storage capacity, which significantly contributes to the stabilization of discharges of springs supplied by such reservoirs. The study carried out in karst areas of the Kłodzko Land showed the values of the recession coefficient α to be at the same level as in the case of groundwater reservoirs in Cretaceous rocks. As a result of that, the values of the groundwater volume stored were also high, at a level of 400-500,000 m^3. On the other hand, a similarity between karst reservoirs and reservoirs formed in weathered and fractured mica schists and gneisses is the water residence time in the aquifer system, which is on average one hundred and several dozen days and which is much shorter than in the case of Cretaceous rocks.

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