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Determination of catchment-scale hydrogeological parameters of fractured crystalline rocks using streamflow recession analysis – an example from south-western Poland

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Abstract: To estimate catchment-scale hydrogeological parameters such as hydraulic conductivity (*k*) and specific yield (*Sy*), the streamflow recession analysis method proposed by Brutsaert and Nieber (1977) was used. The analysis employed the technique of fitting a theoretical recession curve to the observed data in which three points of transition between the short- and long-term flow regimes were determined. This method is a simple, fast, and cheap alternative to standard point-based hydrogeological methods using investigations carried out in hydrogeological boreholes. The study area covered the mountainous catchment of the Biała Lądecka River, located in south-western Poland and composed of metamorphic rocks. The hydrogeological environments drained by the Biała Lądecka are two zones, i.e. the zone of weathered covers and rock debris and the zone of fractured rock mass. The *k* values determined based on the recession analysis were in the boundary zone of the range from 10^{-4} to 10^{-5} m/s and they represented the upper range of the values reported in the literature (from 10^{-4} to 10^{-7} m/s). The *Sy* values at a level of 0.38–1.02%, in turn, entirely fitted the literature data. The results confirm the thesis that the recession method, despite certain limitations in terms of its applicability, can be well adapted to the conditions of a mountainous catchment composed of crystalline rocks where a cool temperate climate prevails.

Keywords: recession flow analysis, hydrogeological parameters, mountainous terrain, Poland, fractured-flow

INTRODUCTION

The management of water resources during the current period of global climate change, particularly in areas affected by water deficit, is becoming an important element of socio-economic policy. In Poland's mountainous areas, there are regions with a seasonal deficit of drinking water (Kubiak-Wójcicka & Machula 2020), especially during the summer period due to increased tourist traffic, for example. Currently, this situation is problematic in several regions of the Sudetes (SW Poland), among others in the Kłodzko Land which is the study area. Compared to surface water resources, groundwater resources are usually considered to be less susceptible to climate change (Döll 2009, Olichwer & Tarka 2015), but socio-economic development also leads to a continuous increase in the demand for groundwater. It is therefore important to conduct appropriate water resources management and exactly identify water resources drivers (Thomas et al. 2013).

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In the case of water resources management at a river catchment scale, knowledge of the hydrogeological parameters that determine groundwater discharge is necessary. In Poland's mountainous areas, groundwater discharge accounts for about 50% and more of the river flow (Staśko et al. 2010, Olichwer 2019), which makes up a significant component of total water resources. During periods of atmospheric drought and a lack of surface runoff, groundwater discharge is the only source of river supply. In particular, hydraulic conductivity (k), specific yield (Sy) and aquifer thickness are of major importance to estimate groundwater resources. Hydrogeologists, especially in mountainous areas, must frequently cope with the lack of available hydrogeological data for large areas, which leads to uncertainties associated with groundwater discharge calculations. The determination of the hydrogeological parameters of crystalline rocks in mountainous areas is particularly hindered due to the high costs related to drilling of piezometers and conducting hydrogeological investigations (pumping tests) in difficult topographic conditions. Given the above, few such investigations are carried out and they are usually concentrated in the valley zones of rivers draining fractured crystalline rock masses. For instance, in the catchment of the Biała Lądecka River (SW Poland) comprising the study area, there are only four hydrogeological boreholes where the hydraulic conductivity of the fractured crystalline rock mass has been determined based on a pumping test. There is a lack of reliable characteristics of the hydrogeological parameters of areas located further from the main river axis, e.g. slope areas of mountainous catchments composed of fractured bedrock covered by a weathering crust. Furthermore, some catchment-scale hydrogeological parameters such as, e.g., transmissivity (T) are characterized by high variation of observed values (several orders of difference), while sporadic point-based measurements using field or laboratory tests can give misleading results which are not consistent with the average values for an entire catchment (Zecharias & Brutsaert 1988). A solution to these problems can be an intermediate method of estimating hydrogeological parameters, such as hydraulic conductivity (k) and specific yield (Sy), for an entire catchment based on streamflow recession analysis.

The method using analysis of temporal streamflow recession proposed by Brutsaert and Nieber (1977) was applied in this study to determine aquifer hydrogeological parameters. In this method, the recession analysis is based on the solutions of the Boussinesq equation and it was first used for humid glacial areas with a moderate topography in the state of New York. This method was developed further thanks to the studies of Troch et al. (1993), Brutsaert (1994), Parlange et al. (2001) and Mendoza et al. (2003), among others. Subsequent studies showed that this method could be successfully used in less humid regions with a more diverse topography (Brutsaert & Lopez 1998). Positive results were also recorded in humid mountainous areas composed of diagenized sedimentary rocks (Zecharias & Brutseart 1988, Parlange et al. 2001). Troch et al. (1993) successfully used this method in eastern Flanders (Belgium) where there is a humid climate. Good correlations between the results of field hydrogeological investigations and recession analysis results for karst upland areas with large terrain slopes are confirmed by a study from the Philippines (Malvicini et al. 2005). Furthermore, a study from Mexico by Mendoza et al. (2003) demonstrated that the above specified recession method performs well for semi-arid mountainous areas composed of eroded and fractured volcanic rocks. This method was also applied for fractured crystalline rock areas in a dry climate of Oman (Dewandel et al. 2003) and in dry mountainous areas of Chile (Oyarzún et al. 2014). Areas in which the method in question has also been used include Mediterranean regions (southern France) composed of crystalline rocks covered by less permeable soil horizons of large thickness (Vannier et al. 2014). A study by Senkondo et al. (2017) in Tanzania showed that this method could be successfully used in crystalline rock areas in a sub-humid tropical climate with a long rainy season, but it was also employed in the case of a tropical monsoon climate of Taiwan (Huang & Yeh 2019).

In the last 20 years, the recession method of Brutsaert and Nieber (1977), with modifications, has been widely used in many regions of the world with diverse climatic, geological, and topographic conditions. In all of the above cited examples, the indirectly estimated hydrogeological parameters were consistent with the direct field or laboratory measurements. The aim of this study was to determine how well the recession method performs in an area that is more different climatically and geologically than the previously studied areas. To estimate average hydrogeological parameters, a mountainous catchment composed of fractured and weathered metamorphic rocks (gneisses, schists) was selected. A cool temperate climate, with the mountain climate characteristics, prevails in this area. This is a type of catchment that has never been analyzed in the literature thus far. Moreover, determination of hydrogeological parameters of a fractured rock mass environment using borehole methods is particularly difficult and costly and therefore application of an intermediate method, such as the flow recession analysis, can be a cheaper and more available alternative.

STUDY AREA

The study area is located in the Sudetes in the south-western part of Poland and covers the Biała Lądecka River catchment with an area (A) of 164 km^2 downstream to the hydrometric cross section in the town of Lądek-Zdrój (Fig. 1).

The area drained by the river is forested mountainous terrain (the forest cover rate is 74.8%) located at an elevation range of 420–1,425 m a.s.l. The average catchment elevation is 735 m a.s.l. The catchment gradient is 7.5%. The spring zone of the Biała Lądecka River is situated at 1,090 m a.s.l. The catchment perimeter (P) is 69.6 km. The Biała Lądecka flows in a deeply incised, meandering and forested valley with a length of 29.1 km. The river valley gradient is 2.3%. The catchment compactness index (Kc) is equal to 1.53, which means a trend towards an elongated shape of the catchment. The average total discharge from the Biała Lądecka River catchment (downstream to the hydrometric cross section in Lądek-Zdrój) for the long-term period 1966–2005 was 3.56 m^3/s. During the summer period (from May to October), the total discharge was 3.94 m^3/s, whereas in the winter period (from November to April) it was 3.18 m^3/s (Olichwer & Tarka 2015). The study area is characterized by a high percentage of groundwater discharge in the total discharge, standing at 70–80% (Staśko et al. 2010). The average value of the groundwater discharge for the long-term period 1966–2005 is 17.77 $L/(s \cdot km^2)$ (Olichwer & Tarka 2015).

The climate in the study area is temperate, cool, and mountainous, with four main seasons of the year. In the upper parts of the catchment studied, the annual precipitation (rain, snow) exceeds 1,600 mm, whereas in the lower situated areas it is 800–900 mm per year. Most precipitation occurs in summer months, i.e. June and July (about 140 mm per month) (Staśko & Tarka 2002). The percentage of snowfall in the total precipitation ranges 20–40% (Staśko & Tarka 2002). Snow cover persists up to 150 days in a year (Olichwer & Tarka 2015). The mean annual temperature of the study area is in the range from 2.5°C (1,200–1,400 m a.s.l.) to 7.1°C (400–500 m a.s.l.) (based on data of the Institute of Meteorology and Water Management, Warsaw).

In terms of geological conditions, the study area is composed of Paleozoic metamorphic rocks dominated by schists and gneisses (Fig. 1) covered by an almost continuous mantle of weathered and rock debris deposits (Żelaźniewicz et al. 2002). Alluvial sediments, characterized by a varying width from about 50 m to almost 550 m, are found in the valley of the Biała Lądecka River in its middle and lower course. The total thickness of fluvial sediments does not exceed 2 m. The area of alluvial sediments (3.5 km^2) is small relative to the entire catchment area (about 2%).

Three groundwater zones with different hydraulic conductivity properties and recharge and drainage conditions occur in the study area (Fig. 2). Weathered covers found on planation surfaces and slopes in the upper parts of the area, with an average thickness of 2–5 m, are associated with the shallowest zone. This zone is characterized by a high specific yield (Sy = 0.18) and a low hydraulic conductivity (k = 0.1 m/d). Densely fractured metamorphic rocks with a higher hydraulic conductivity (k = 1–5 m/d) and a low specific yield (Sy = 0.008–0.03) are found below. The thickness of this zone reaches 50–60 m. Groundwater from these two zones, discharged into the river channel, appears in the Biała Lądecka River. The third zone, reaching to 500 m below ground level, consists of deep faults forming deep water circulation paths of regional significance.

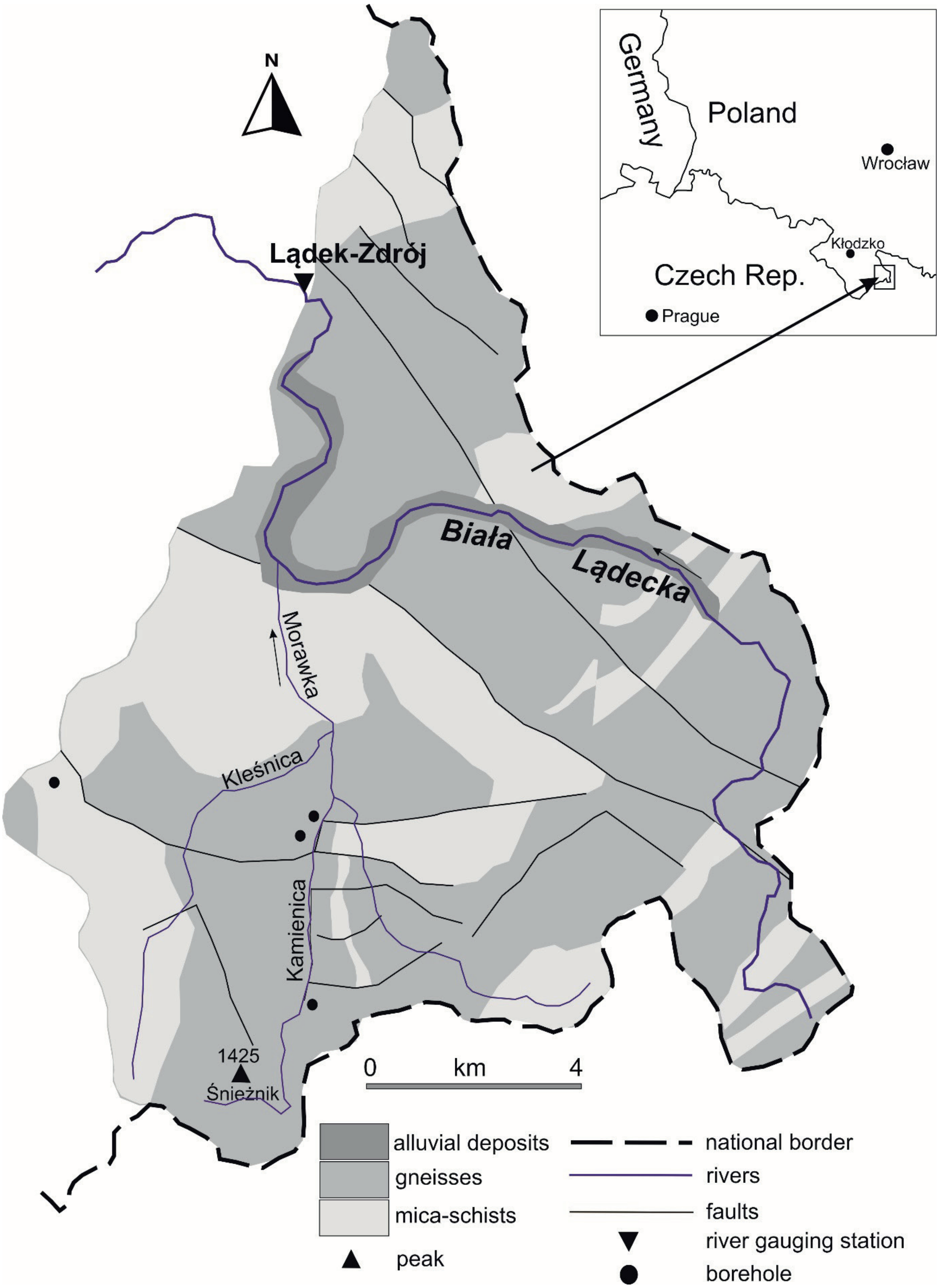

Fig. 1. *Study area with geological background (based on Sawicki red. 1966)*

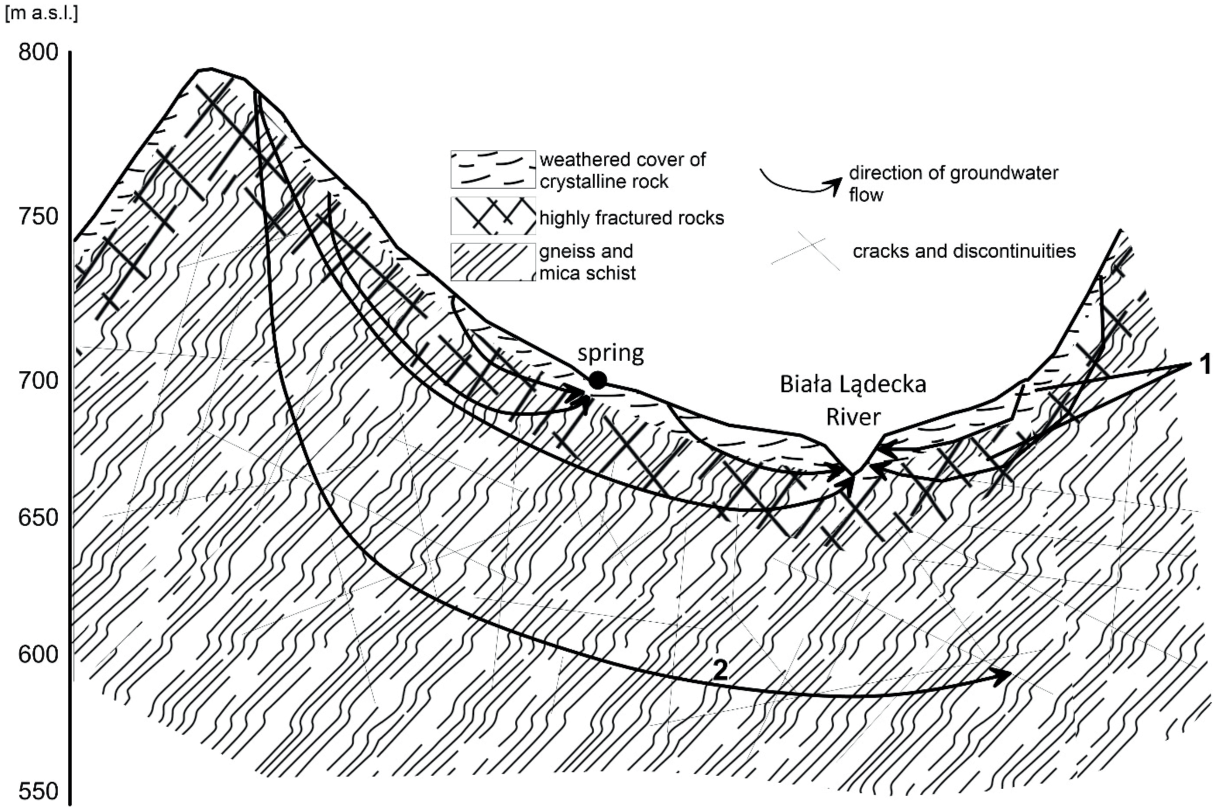

Fig. 2. *Scheme of groundwater circulation in the active exchange zone in crystalline rocks of the study area: 1 – weathered and cracked rock massif, 2 – zone of deep groundwater circulation*

The specific yield and hydraulic conductivity of the rocks associated with this zone are the lowest (Sy = 0.0001–0.001, k = 0.001–0.1 m/d) (Staśko 2002). The third zone is drained by higher order rivers than the Biała Lądecka. Therefore, the weathered and fractured rock mass zones being in hydraulic contact with local faults are an important element in the Biała Lądecka catchment (Pacheco & Alencoão 2002, Earman et al. 2008). Rock fractures are privileged flow paths and provide significant inflows to the river valleys.

METHODOLOGY

The technique of streamflow recession analysis presented by Brutsaert and Nieber (1977) with subsequent modifications was used to indirectly estimate the hydrogeological characteristics of the water-bearing horizon of the mountainous catchment. These researchers found that there is a relationship between the flow (Q) and its temporal change (dQ/dt) under no precipitation conditions, as shown by Formula (1):

$$dQ/dt = -aQ^b \qquad (1)$$

where:
- Q – recession flow [m^3/s],
- t – time [s],
- a, b – constants for a particular recession flow regime.

In their theory, Brutsaert and Nieber (1977) used the Boussinesq equation. This equation describes drainage of water from an ideal unconfined aquifer with a characteristic width (B). It is assumed that the aquifer is initially saturated, bounded below by a horizontal impermeable layer, and is completely drained by the stream as well as there is no evapotranspiration (Boussinesq 1904).

Assuming that the outflow from an aquifer during a recession period is a function of its hydrogeological characteristics, catchment-scale aquifer parameters can be indirectly estimated based on properly prepared data for the recession curve and by determining the relationship between Q and dQ/dt (Parlange et al. 2001, Mendoza et al. 2003, Rupp & Selker 2006). This method also assumes that the streamflow originates from the inflow of water from the aquifer to the stream channel.

Two components are distinguished: the short-term flow regime and the long-term flow regime.

The short-term flow regime is the part of the streamflow that occurs in a short time between precipitation and the inflow of water to the stream channel. Short-time flow regimes have relatively high values of Q and |dQ/dt|. This example is represented by Formula (2) (Mendoza et al. 2003). For the short-term solution, b is equal to 3:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{1.1337}{kSyD^3L^2}Q^3 \tag{2}$$

where:
- k – hydraulic conductivity [m/s],
- Sy – specific yield [–],
- D – aquifer thickness [m],
- L – total length of upstream channel intercepting groundwater flow [m].

In the long-term flow regime precipitation infiltrates into the aquifer and subsequently appears in the river discharge more slowly; this is so-called base flow. The long-term case can be expressed by Formula (3) (Mendoza et al. 2003). It should be noted that b from Equation (1) is equal to 3/2:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{4.8038k^{1/2}L}{SyA^{3/2}}Q^{3/2} \tag{3}$$

where A – watershed area [m^2]

When both flow regimes are represented in a data series, the short- and long-term regimes are visually displayed in the form of the "lower envelope" of the data in the plot log(|dQ/dt|) *vs.* log$Q$. The slump in the envelope lower line (Fig. 3) indicates the point of transition between the short-term and long-term flows with a slope of 1:1.5 and 1:3.

Because appropriate assessment of the transition between the short- and long-term flow regimes can be difficult, Parlange et al. (2001) presented an alternative and mathematically simpler equation. It consists of the dimensionless flow (Q^*) and time (t^*) for a theoretical dimensionless recession curve. In this method, the plot of the log(|dQ/dt|) *vs.* log$Q$ is employed. Based on optimization using the least-squares method, Parlange et al. (2001) found that the point of transition between the two flow regimes is close to the log(Q^*) = −0.1965 and the log(|dQ^*/dt^*|) = 0.0918. Figure 3 shows how the dimensionless recession curve is translated into the data-derived recession curve log$Q$ *vs.* log(dQ/dt).

Thus, to estimate catchment-scale hydrogeological parameters for a specific set of flow recession data, the vertical and horizontal shifts, respectively H and V (Fig. 3), between the theoretical values [log(Q^*), log(|dQ^*/dt^*|)] and data-derived values [log$Q$ *vs.* log(dQ/dt)] are determined.

After the point of transition has been determined and the values H and V have been assigned to it using the above-described Equations (4) and (5), the hydrogeological parameters such as k, Sy and D can be estimated for the entire catchment (Parlange et al. 2001, Mendoza et al. 2003):

$$H = \frac{kAD^2}{B^2} \tag{4}$$

$$V = \frac{k^2AD^3}{SyB^4} \tag{5}$$

where B – catchment width [m], $B = A/2L$, where L is the total length of stream channel.

Due to this approach, recession flows based on daily flows of the Biała Lądecka River in the hydrological period 1981–2021 were prepared during the first stage. The daily flow data were obtained from the Institute of Meteorology and Water Management (IMGW). Sequences of the river flow decreasing over time were selected in such a way so as to separate the percentage of surface discharge and take into account only the outflow from the aquifer (base flow). To effectively select flows during recession, which are a pure low flow, all daily flow data that coincided with precipitation periods were excluded. Moreover, daily data sequences showing 4 or more days of recession, at least 3 days after the end of a precipitation event, were used. In this way, 549 flow recession periods were generated for the study area, which gives about 13 periods during one hydrological year.

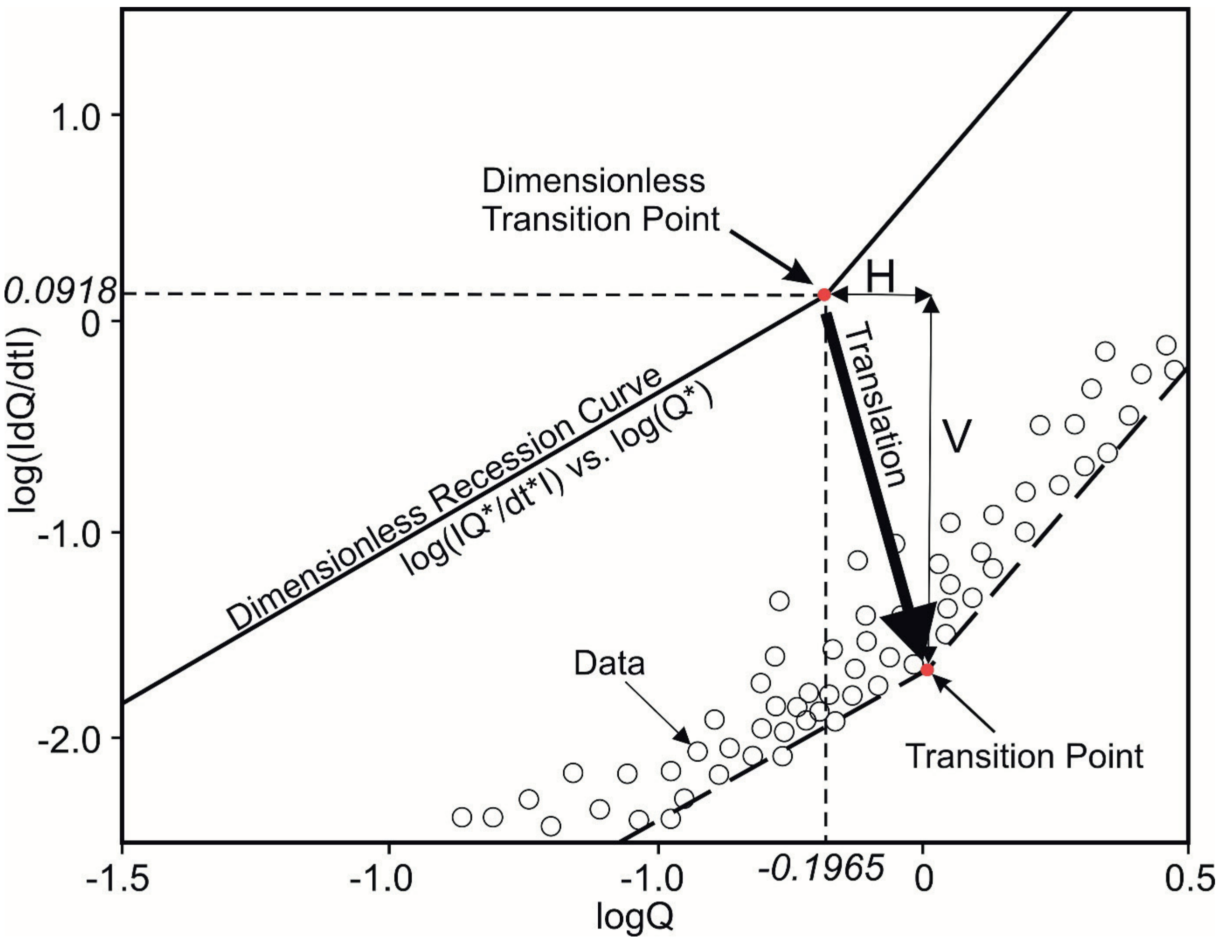

Fig. 3. *Schematic diagram showing the location of the dimensionless recession curve relative to the recession flows of the catchment in question. The dimensionless and observed points of transition, which allow determination of the vertical shift V and horizontal shift H, are also shown (Mendoza et al. 2003)*

On average, the recession periods lasted 6–8 days, while the maximum period was 50 days (October – November 2003). Next, a pair of data was designated for each recession period as $\log(|dQ/dt|) = \log[(Q_p - Q_k)/dt]$ *vs.* $\log Q = \log[(Q_p + Q_k)/2]$, where Q_p and Q_k represent the flow expressed in cubic meters per second (m^3/s) at the beginning and end of the recession, while d*t* is the time in seconds between the two points. This approach, applied by Brutsaert and Lopez (1998), simplifies the analysis because the theoretical relationship from Equation (1) becomes linear $\log(|dQ/dt|) = b \log Q + \log(a)$. The 549 pairs of data were presented in a plot where the log*Q* values were in the X axis and the log(|d*Q*/d*t*|) values in the Y axis in order to parameterize the base recession characteristics.

In the obtained plot, it is difficult to unambiguously determine the actual location of the point of transition between the short- and long-term regimes. Therefore, for the purpose of this article, the method proposed by Mendoza et al. (2003) was employed.

It is based on consideration of three possible transition points that were identified as follows:

1) The first transition point: The intersection of the lower envelope lines of the short-term flow regime ($b = 3$) and long-term flow regime ($b = 1.5$) (Brutsaert & Nieber 1977). The envelope lines were placed in such a way that 10% of the data points were below these lines in order to reduce the impact of evapotranspiration (Malvicini et al. 2005). Point 1 represents the lower boundary of the transition point (Mendoza et al. 2003).

2) The second transition point: The intersection of the linear regression line in the plot dQ/dt *vs.* Q and the lower envelope for b = 3. This point represents the intermediate location of the transition point.
3) The third transition point: The intersection of the upper envelope for b = 1 with the vertical line based on the highest value of log$Q$ among the data points. This point means the upper boundary of the flow recession.

According to Mendoza et al. (2003), transition point 2 is the point that best reflects estimation of hydrogeological parameters, while points 1 and 3 represent measures of uncertainties in the estimation of parameters.

During the next stage, the theoretical recession curve (Parlange et al. 2001) (Fig. 3) for the observed data was compared with the three determined points of transition between the short- and long-term regimes as well as the value of horizontal (H) and vertical (V) translation was determined for each of the points:

$$Sy = \frac{H^2}{V} A \cdot D \tag{6}$$

$$k = \frac{V \cdot Sy \cdot B^2}{H \cdot D} \tag{7}$$

The known H and V values and the transformed Formulas (6) and (7) (Oyarzún et al. 2014) were used to determine two hydrogeological parameters, i.e. hydraulic conductivity (k) and specific yield (Sy), whereas aquifer thickness (D) was taken from the literature. Because there are two equations and three unknown hydrogeological parameters, it is necessary to make a reasonable estimation of one of these three parameters. Aquifer thickness (D) is the best identified parameter for the catchment area of the Biała Lądecka River and it is characterized by the lowest uncertainty and variation relative to the other hydrogeological parameters. Due to this, hydraulic conductivity (k) and specific yield (Sy) can be estimated as functions of aquifer thickness (D) (Mendoza et al. 2003, Parlange et al. 2001).

In the case of other catchments for which the parameter D is not known but where the specific yield (Sy), for example, is well identified, we are able to determine transmissivity (T) and thickness (D) using Equations (8) and (9) (Mendoza et al. 2003):

$$T = \frac{V}{H} SyB^2 \tag{8}$$

$$D = \frac{H^2}{V} \frac{1}{SyA} \tag{9}$$

where T – transmissivity [m^2/s].

RESULTS AND DISCUSSION

The area of the mountainous catchment studied is characterized by an elongated shape and a distinct river channel with a small proportion of alluvium relative to the entire catchment area.

The temporal changes in streamflow are typical for mountainous areas with a cool temperate climate of Central Europe. An increased flow occurs in the early spring months (March – April) as a result of snow cover melting and during summer months (June – July) due to significant rainfall. Low water flows, in turn, coincide with the late autumn and winter period (November – February). The maximum flow of 270 m^3/s was recorded during the flood in July 1997 (Fig. 4). The average Q values range 3–4 m^3/s, whereas low water levels correspond to Q values below 1.5 m^3/s.

Figure 5 displays the plot log(|dQ/dt|) *vs.* log$Q$ for the Biała Lądecka River catchment, whereas Table 1 presents the values of the flow regime points [log$Q$, log(|dQ/dt|)] and the horizontal (H) and vertical (V) shift for each plotted distribution of the transition points.

The linear regression slope (Fig. 5) shows generally the average recession constant (b) for the entire catchment, facilitating the identification of the dominant flow regime. The study area exhibits a linear regression slope of 1.66 which is close to the theoretical slope of 1.5. This means that the long-term flow regime is predominant in the points in Figure 5. Similar flow properties were previously observed for long-term flow data from much more humid, mildly sloping catchments as well as from semi-arid mountainous catchments. This has now also been confirmed in the case of a mountainous catchment with a cool temperate climate of Central Europe.

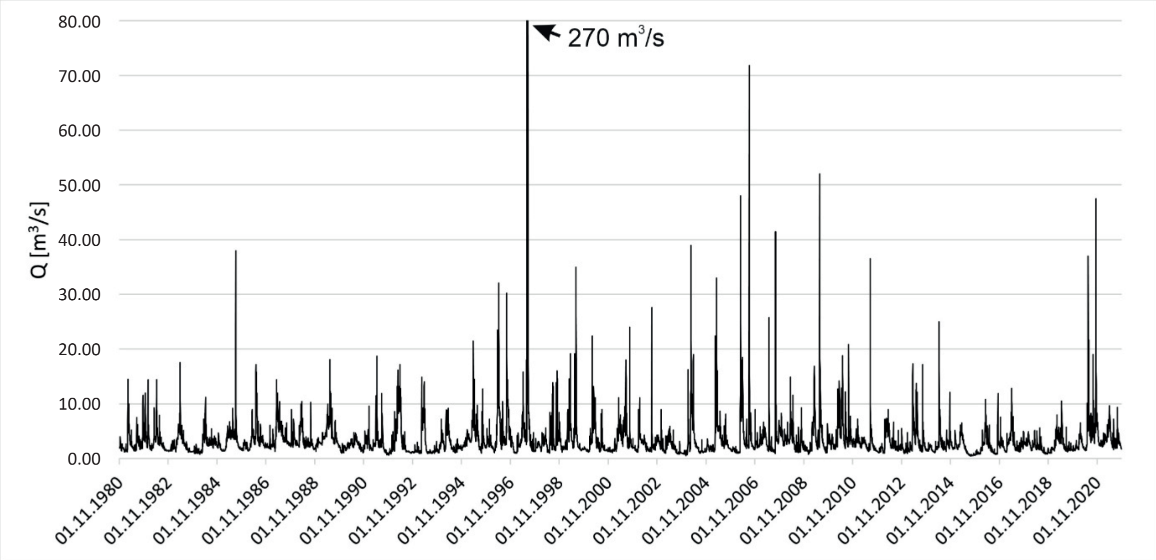

Fig. 4. *Discharge time serie of Biała Lądecka River (data source: Institute of Meteorology and Water Management – National Research Institute)*

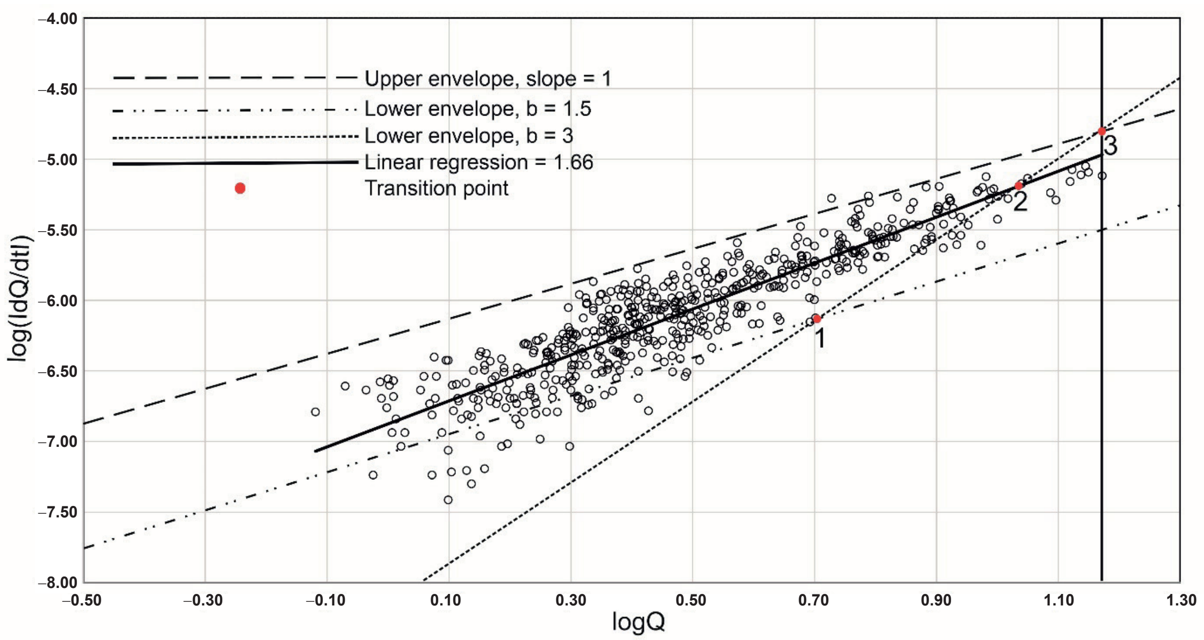

Fig. 5. *Recession flow data from Biała Lądecka River with transition points 1, 2, 3 (based on processed data) (source basic data: Institute of Meteorology and Water Management – National Research Institute)*

Table 1
Coordinates of flow regime transition point [logQ; log(|dQ/dt|)] and values for the horizontal (H) and vertical (V) translations for each placement strategy

log*Q*; log(d*Q*/d*t*)			***H*** **[m³/s]**			***V*** **[·10⁻⁷ m³/s²]**		
1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
0.67; −6.20	1.02; −5.23	1.17; −4.79	7.25	16.40	23.50	5.14	47.80	144.00

1, 2 and 3 – transition points.

The hydrogeological parameters for the entire catchment calculated based on the horizontal (H) and vertical (V) shift of transition points 1, 2 and 3 are presented in Table 2. According to Mendoza et al. (2003), the parameters from transition point 2 are considered to be the probable estimated values of k and Sy.

Table 2
Summary of hydraulic conductivity and specific yield estimation

k [m/s]			**Sy** [%]		
1	**2**	**3**	**1**	**2**	**3**
$9.90{\cdot}10^{-5}$	$2.25{\cdot}10^{-4}$	$3.19{\cdot}10^{-4}$	1.02	0.56	0.38

1, 2 and 3 – transition points.

The hydraulic conductivity results obtained for the entire catchment based on the flow recession analysis (Table 2) are in the boundary zone of the range from 10^{-4} to 10^{-5} m/s, thus indicating medium permeability of the weathered and fractured rock mass. It is interesting to compare the hydraulic conductivity results obtained in the present study with the values given in the literature. Based on results of pumping tests carried out in three 30 m deep boreholes drilled in the Kamienica River catchment (Fig. 1), the obtained k values were equal to $1.7{\cdot}10^{-4}$, $2.9{\cdot}10^{-5}$ and $2.19{\cdot}10^{-6}$ m/s (Staśko & Tarka 2002). All the boreholes were located in the stream valley in the weathered and fractured gneiss zone. However, the borehole with the result 10^{-6} was located in the upper course of the river, whereas the other two boreholes in the mouth sections of the Kamienica River. On the other hand, in one 30 m deep borehole drilled through fractured schists in the western part of the Biała Lądecka River catchment (Fig. 1), the k value was recorded to be $1.12{\cdot}10^{-6}$ m/s based on a pumping test. A field study conducted by Staśko and Tarka (2001) in the Kamienica River catchment, in turn, found the average value of the hydraulic conductivity of weathered gneisses and schists to be at a level of 10^{-5} m/s. A subsequent field study of hydraulic conductivity in the Kamienica River catchment based on rock fracture measurements showed the k value to range from $3.8{\cdot}10^{-4}$ to $1.1{\cdot}10^{-7}$ m/s (Szczepanowski & Staśko 2001). Taking into account the areas for which hydrogeological information is available (i.e. the Kamienica stream), the flow recession analysis gives the k values that are within the upper range of the values reported in the literature where the average values range from 10^{-4} to 10^{-7} m/s. This can be explained by the fact that the literature data come from a small sub-catchment of the study area (the Kamienica catchment – 7.4 km^2), located in its upper part. It should also be reminded that the values of the hydrogeological parameters derived from the recession analysis are the average values for the entire catchment, whereas the literature data were derived from point-based measurements made at a specific location.

Specific yield (Sy) exhibits distinctly smaller differences. The values obtained from the recession analysis ranging 0.38–1.02% are substantially in agreement with the Sy values from the literature. This is confirmed by the study conducted by Staśko and Tarka (2002) in the Kamienica River catchment where Sy for fractured gneiss rocks was in the range of 0.23–1.35%. On the other hand, the studies carried out in other areas of the Sudetes where metamorphic rocks are found indicated a low specific yield of the fractured rock mass, with the Sy values ranging 0.8–3.0% (Staśko 2002, Modelska et al. 2015).

The slightly divergent results for hydraulic conductivity (k) obtained in this study relative to the literature data are due to the fact that two hydrogeologically different zones, i.e. the zone of weathered clays and rock debris and the zone of fractured rock mass, are the hydrogeological environments drained by the Biała Lądecka River. The first zone is characterized by a high specific yield and a low hydraulic conductivity. The other deeper zone, on the other hand, is characterized by a higher hydraulic conductivity and a much lower specific yield. Therefore, the hydrogeological parameters obtained from the recession analysis are a derivative of the characteristics of the above-mentioned two zones.

The results presented in this paper confirm the idea that the Brutsaert and Nieber (1977) method, with its subsequent modifications, can be well adapted to the conditions of a mountainous catchment composed of crystalline rocks where a cool temperate climate prevails, despite the fact that it does not meet all the requirements of the applicability of the Boussinesq equation (e.g. existence of evapotranspiration). Many earlier studies (Mendoza et al. 2003, Malvicini et al. 2005, Stoelzle et al. 2013, Oyarzún et al. 2014, Huang & Yeh 2019) have found that the existence of evapotranspiration is only limited to the initial period of recession (1–2 days after a precipitation event). Hence, in the preparation of input data for the flow recession analysis and estimation of the hydrogeological parameters for the entire catchment, an attempt was made not to include the short-term regime. In effect, when a part of the data is rejected from the analysis, contradictions with some of the assumptions become ultimately irrelevant. It should be remembered that the method employed gives probable values of the hydrogeological parameters (k, Sy, D) for a catchment where there is no hydrogeological identification, or it is poor and limited to a small area. Moreover, in the case of catchments that have a similar geological structure and hydrogeological conditions as the one in the study area, it is most reasonable to determine k and Sy based on the adopted value of D. Aquifer thickness is the least varying parameter (up to the first order of magnitude) and it is easiest to determine its value, e.g. based on terrain morphology (Oyarzún et al. 2014).

CONCLUSION

In this article, the flow recession analysis method proposed by Brutsaert and Nieber (1977) was used to estimate hydrogeological parameters. The analysis was based on daily river flows selecting recession periods predominantly representing the long-term flow regime.

According to the literature, this method gives good results in catchments characterized by a horizontal impermeable aquifer, entirely drained by a stream, in flat and humid regions, but also in semi-arid areas. The article applies this method to a slightly different catchment, such as the one located in south-western Poland. Apart from being climatically different, the catchment under study has a complex geometry and slopes steeply. Despite this divergence, good results were obtained in the evaluation of hydrogeological parameters such as hydraulic conductivity (k) and specific yield (Sy).

An advantage of the applied method is that hydrogeological parameters can be estimated in a simple, fast, and cheap way with respect to areas where there is no hydrogeological information. It should be remembered that data regarding daily precipitation and river flows in a catchment are necessary in this recession method. However, many weather stations are located in Poland's mountainous areas and these data are generally available for small-area catchments. Thus, this method can be a possible alternative to field methods whose use can be impossible or substantially hindered due to logistics and high costs relative to the set research goal. The obtained average values of hydrogeological parameters can be used, for instance, in regional-scale studies of water resources or in the management of these resources at the administrative level. Moreover, the estimated parameters can be used as initial hydrogeological information in further detailed field investigations.

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