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Flow Duration Curves for Two Small Catchments with Various Records in Lowland Part of Poland

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1. Introduction

A flow duration curve (FDC) provides the percentage of time (duration) a daily or monthly stream flow is exceeded over a historical period for a particular stream gauge [7, 16 and 17]. It is the principal means for summarizing the hydrological characteristics of a river [13 and 19]. FDCs are widely used by hydrologists and hydro-engineers around the world in numerous water related applications like hydropower generation and planning and design of irrigation systems, predicting droughts, management of stream-pollution, river and reservoir sedimentation and fluvial erosion [1, 4–6, 9, 10, 12]. This common need is a driving force for many investigations to develop FDCs for ungauged catchments [8, 11, 15, 18]. They are, however, carried out for larger catchments, as number of small catchments with long term hydrological monitoring is very limited. As FDC of small catchment are very sensitive to local physiographical characteristics i.e. land use, geology, topography, so investigations in such areas are very valuable and needed.

The aim of the investigation was to estimate FDCs for two small agricultural catchments, located in south part of Mazovia (center of Poland), with different records of daily discharges. One of the catchment has long term (48 years) record of daily discharges (donor catchment), whereas the other one (partially gauged catchment) was monitored during 2.5 years only.

2. Characteristics of the investigated area

2.1. Location and main parameters of the two catchments

These two catchments are the Zagożdżonka River and the Zwoleńka River. They are located in central part of Poland, ca 100–130 km south of Warsaw (Figure 1). The catchments border on each other and both rivers are left tributary to the Vistula River at its middle reach. The Zagożdżonka River, with its outlet near Kozienice town (N:51º39'28"; E:21º29'13"), has long-term daily flow record at the stream gauge Płachty Stare (N:51º26'43.8"; E:21º27'35.6"), which is located upstream of Pionki town, and is closing catchment area of 82.4 km^2. The Zwoleńka River, bordering on south-east to the Zagożdżonka River, has its outlet at Borowiec village (N:51º16'16.6"; E:21º49'24.2").

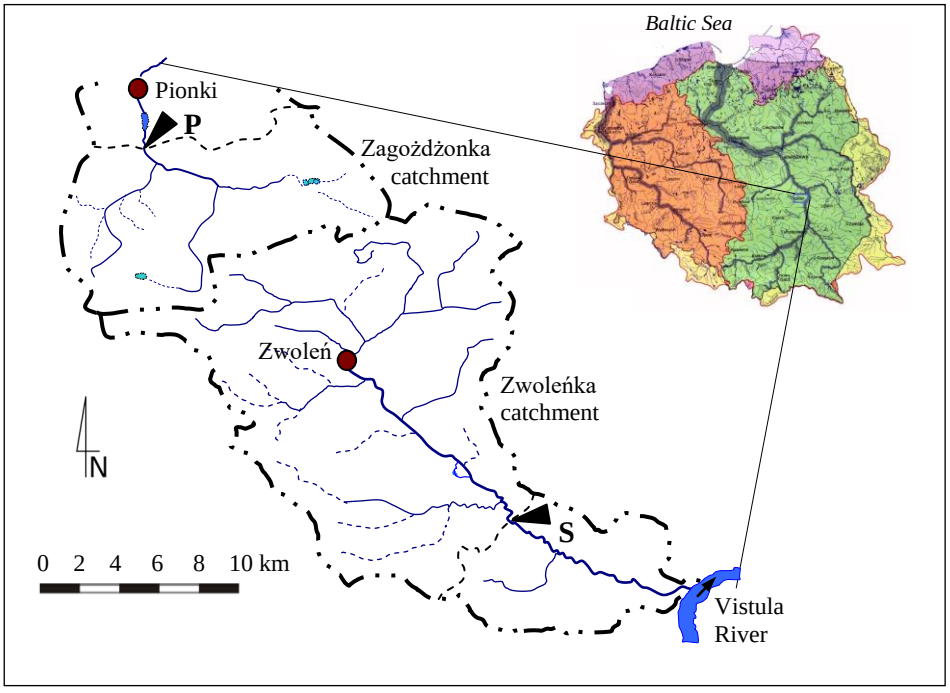

Fig. 1. Locality map of Zagożdżonka catchment, with the river gauge Płachty Stare (P) and Zwoleńka catchment, with the river gauge Siekierka (S)
Rys. 1. Mapa lokalizacyjna zlewni rzeki Zagożdzonka z profilem badawczym Płachty Stare (P) i rzeki Zwoleńka z profilem badawczym Siekierka (S)

The river gauging station of Siekierka (N:51º17'25.0"; E:21º41'42.2") is located within the "Natura 2000" area, ca 7.0 km upstream of the Borowiec Nature Reserve (measured along a straight line), and is closing catchment area of 186.8 km^2. Main characteristics of the catchment of the Zagożdżonka River at Płachty Stare gauge and on the Zwoleńka River at Siekierka gauge are given in Table 1. Both catchments are characterized by agricultural use, with forested area of ca 40% in Zagożdżonka catchment and 24% in Zwoleńka catchment.

Table 1. Main characteristics of the analysed catchments
Tabela 1. Główne charakterystyki analizowanych zlewni

No	Category	Zagożdżonka River at Płachty gauge	Zwoleńka River at Siekierka gauge
1.	Area – A (km^2)	82.4	186.8
2.	Length of the main river – L (km)	11.7	25.2
3.	Main river slope – J (m/km)	2.37	1.63
4.	Mean catchment slope – Ψ (m/km)	4.08	3.66
5.	Shape factor SH defined as the drainage area divided by the square of the main channel length – A/L^2 (-)	0.60	0.29
6.	Ratio of forest area (-)	0.40	0.24
7.	Width and soil of the river valley, river channel plan	narrow valley with organic soils, usually straight river channel	wide valley (up to 200–400 m), with organic & peat soils, often meandering river, specially in its lower reaches
8.	Continuous discharge record	Long term (48 years)	Short term (2,5 years)
9.	Gauging cross section	channel	bridge

Both rivers are classified as lowland once, however main channel of the Zagożdżonka River is a bit steeper (on average ca 2.37‰) than the one of the Zwoleńka River (1.63‰). Shape factor, characterizing the process of flood flow formation, and defined as the drainage area divided by the square of the main channel length is 0.60 for Zagożdżonka and 0.29 for Zwoleńka. There are also differences in soil of the river valley as well as in the river channel plan. In case of the Zagożdżonka River there is mainly narrow valley with straight river channel, and in case of the Zwoleńka River the valley is wider, often up to 200–500 m, with peat soils, and often meandering stream. The river gauging sites of both rivers are shown on Figure 2 and 3. Data used in this analyse were collected during field investigations, which were carried out in the Płachty Stare gauge for the period of 48 hydrological years (1963–2010), and in the Siekierka gauge for two and half years (i.e. since July 2008 until December 2010).

The Zwoleńka valley belongs to the most valuable natural treasures of Mazowsze region. There are number of habitats protected by "Natura 2000" program within the site and numerous rare plant and animal species. The symbol of the area is European pond turtle appearing in the Borowiec Nature Reserve, i.e. in the valley of lower course of the Zwoleńka River [14]. This has been the main reason to undertake the investigation of hydrological characteristics of the river in 2008, which had not been monitored earlier.

2.2. Precipitation and runoff – source of data for analyse

The hydrometric monitoring and hydrological investigations have been carried out in Płachty Stare on the Zagożdżonka River by the Department of Water Engineering of Warsaw University of Life Sciences since 1962. In the first period, the river water stages have been recorded by an observer, who was reading staff gauge three times a day, except flood periods when reading was usually carried out each hour. Since 1980 monitoring of the river stages has been carried out with the use of mechanical water stage recorder, and since middle of last decade of the previous century with the use of electronic system for recording, logging and transmitting the data. In the recent periods, the traditional reading of staff gauge has been continued for correcting the records once a day.

Fig. 2. The stream gauge at Płachty Stare on the Zagożdżonka River
Rys. 2. Profil pomiarowy w Płachtach Starych na Zagożdżonce

Fig. 3. The stream gauge at Siekierka on the Zwoleńka River
Rys. 3. Profil pomiarowy w Siekierce na Zwoleńce

For precise estimation of river flow a rating curve has been established and verified at least once a year based on hydrometric measurements, which were undertaken 8–12 times each year. The mean daily river flows were a base for further flow duration curve estimation and evaluation.

Based on the precipitation and river discharge data collected within Zagożdżonka catchment for the hydrological years 1963–2010, except precipitation data for the period 1963–1982, which were taken from available publications of the Polish hydro-meteorological service (IMGW) for the nearest rain gauge; Zwoleń (located about 13 km south-east of the Płachty Stare gauging station), the mean annual values of the characteristics were established as 611 mm and 106 mm, respectively. Annual values of precipitation and runoff are shown in Fig. 4.

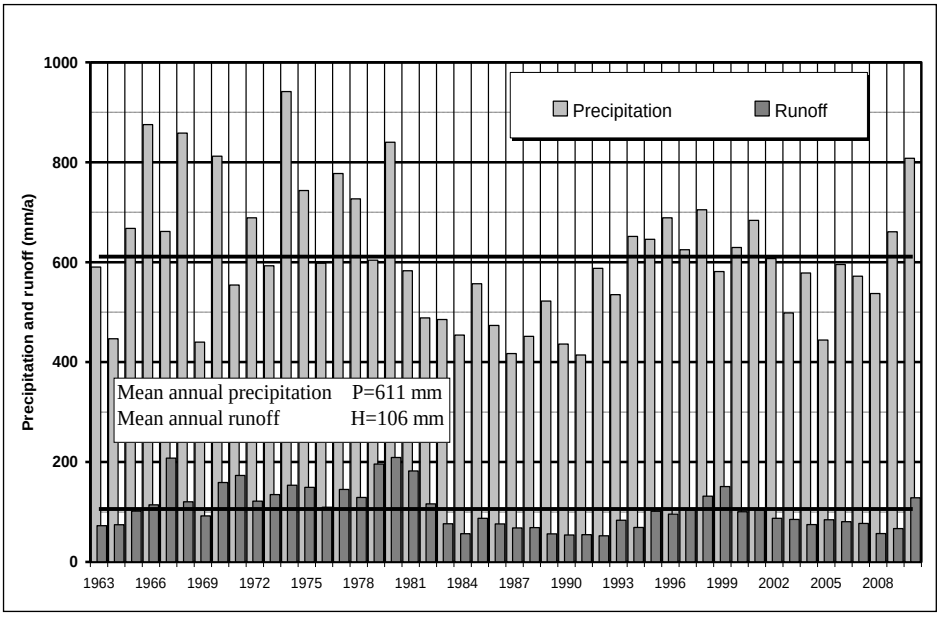

Fig. 4. Annual precipitation and runoff depths for the Zagożdżonka catchment upstream of Płachty gauge for the hydrological years of 1963–2010

Rys. 4. Roczne warstyw opadu i odpływu dla zlewni Zagożdzonki do profilu pomiarowego Płachty Stare w okresie lat hydrologicznych 1963–2010

The maximum and minimum values of annual precipitation are 941 mm (in 1974) and 414 mm (in 1991), respectively. Maximum annual runoff of 209 mm was measured in 1980, and the minimum of 52 mm was measured in 1992. Annual runoff coefficients (ratio of runoff to precipitation) for the area to the Zagożdżonka catchment range from 0.088 (1992) to 0.320 (1979), with a mean value of 0.173.

3. Flow duration curve for the two catchments

3.1. Method of estimation

The Flow Duration Curve (FDC) is used here to express the mean, long term variation in river flow over a year for both the Zagożdżonka River at Płachty gauge and the Zwoleńka River at Siekierka gauge. The first one, as described earlier, has long term (48 year) discharge record, whereas the other one has been monitored only during the period of project investigation, i.e. July 2008 – December 2010 [2 and 3]. The FDC shows how flow is distributed over a year. The vertical axis gives the flow and the horizontal one gives the percentage of the year that the flow exceeds the value given on the y-axis. Hence, for example, the FDC can immediately indicate the level of flow which will be available for at least 50% of the year (known as Q_{50}). The flow exceeding the given value for 95% of the year (Q_{95}) is often taken as the characteristic value for minimum river flow. FDCs can be similar for rivers from a region, but can be affected by soil conditions, vegetation cover, and to a lesser extent by catchment shape. They are also modified by man-made reservoirs, abstractions and discharges. A flatter FDC, characterizing more uniform river flow, means that the total annual flow will be spread more evenly over the year, giving useful flow for a longer period, and less severe floods.

The aim of the investigation has been:

- to present results of flow distribution in the small agricultural catchment. It is unique as long-term hydrological monitoring in such catchments, important for understanding formation of flow of various characteristics, are carried out very seldom,
- to demonstrate a method of estimating the long term average FDC for a river partially gauged, i.e. when short term monitoring and hydro-

metric measurement are carried out in the investigated catchment and in the donor catchment

- to check and discuss differences in FDCs of the neighboring two catchments, which may be caused by local physiographic characteristics.

The FDCs for the Zagożdżonka River at Płachty gauge for the two periods 2008–2010 and 1963–2010 (Fig. 5) were discussed in report from the investigation [16]. Comparison of the FDCs have confirmed that the three year period of investigation (2008–2010), as significantly drier in respect of catchment runoff, than average year (see Fig. 4), cannot deliver sufficient information for hydrological characteristics of a catchment, which has not been gauged before, as it was with the Zwoleńka River.

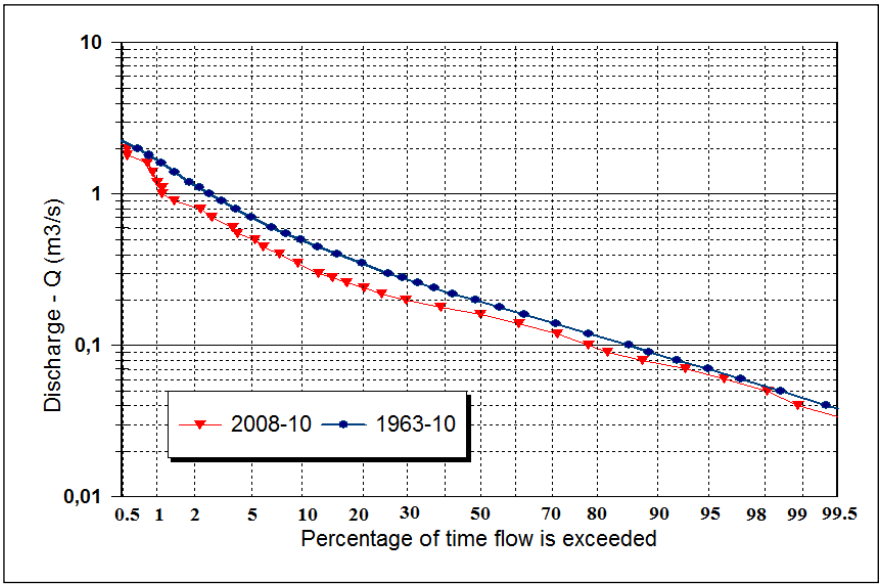

Fig. 5. Flow duration curves of daily discharges for Zagożdżonka river at Płachty Stare gauge for the period of 2008–2010 and 1963–2010
Rys. 5. Krzywe sum czasów trwania przepływów dobowych Zagożdżonki w profilu Płachty Stare w okresie 2008–2010 i 1963–2010

Therefore, the flow duration curve (FDC) for the Zwoleńka River at Siekierka gauge has been constructed by finding relationship between

river discharges of Zwoleńka vs. discharge of Zagożdżonka in the gauging stations, which in turn has been later used for reproducing daily discharges for Zwoleńka, based on long term data of the Zagożdżonka River at gauge Płachty. For constructing the relationship of discharges in the two rivers, 40 corresponding values of instantaneous river flows have been used, from which 26 were semi-simultaneous current meter measurements and 14 were peak flow hydrograph values, estimated on electronic water level records and rating curves. The regression relationship between discharges in the two rivers, shown in Fig. 6, was established as:

$$Q_S = 1.883 \cdot Q_P^{\,0.788} \tag{1}$$

where:

Q_S – discharge of the Zwoleńka River at the Siekierka gauge (m^3/s),
Q_P – discharge of the Zagożdżonka River at the Płachty gauge (m^3/s).

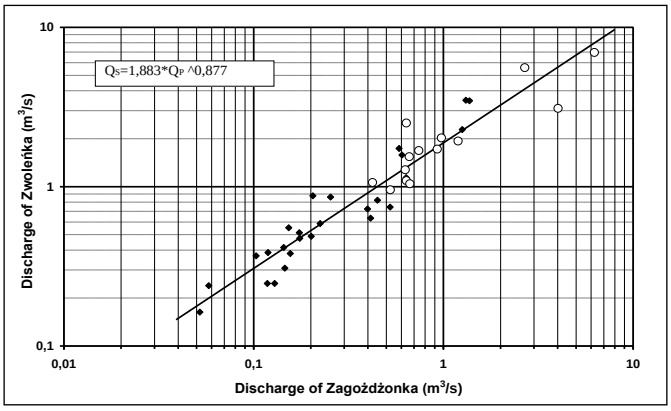

Fig. 6. Corresponding discharges of the Zagożdżonka River at Płachty Stare gauge and the Zwoleńka River at Siekierka gauge estimated on the base of semi-simultaneous flow meter measurements (diamonds) and peak hydrograph records (circles)
Rys. 6. Przepływy korespondujące Zagożdżonki w Płachtach Starych i Zwoleńki w Siekierce ustalone z pomiarów hydrometrycznych (diamenty) i analizy hydrogramów okresów wezbraniowych (kółka)

The determination coefficient, for logarithmic values of discharges, of the relationship 1 is 0.909 (i.e. correlation coefficient r=0.95 with $r_{critical}$=0.31 at 95% level of significance).

3.2. Discussion of the results

Mean annual FDC for the Zwoleńka River at Siekierka gauge, established on the base of long term daily discharges of Zagożdżonka at Płachty and the relationship 1, has been unified to specific discharges. Selected ordinates of FDCs, some of which are presented in Table 2 (column 2 and 3), were transformed to specific discharges for both rivers, according to formula:

$$q_p = \frac{1000 \cdot Q_p}{A} \tag{2}$$

where:

q_p – specific discharge at the pth percentile (dm^3/s/km^2),
Q_p – discharge at the gauge at pth percentile (m^3/s),
A – catchment area, upstream of the gauge (km^2).

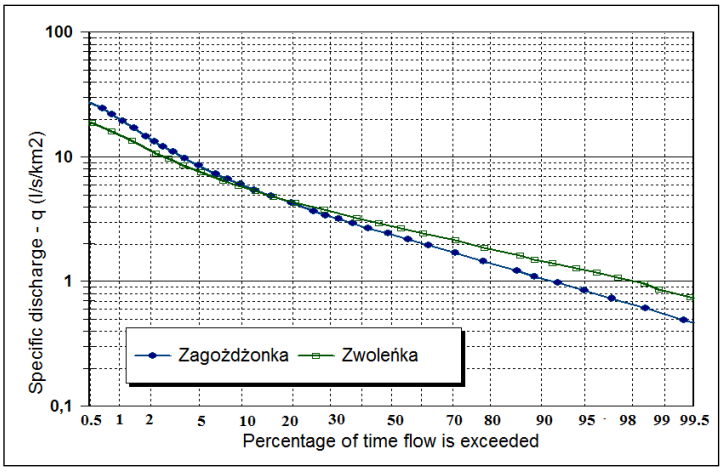

Fig. 7. Flow duration curves of daily specific discharges for Zagożdżonka catchment at Płachty gauge and for Zwoleńka catchment at Siekierka gauge for the period of 1963–2010
Rys. 7. Krzywe sum czasów trwania odpływów jednostkowych Zagożdzonki w Płachtach Starych i Zwoleńki w Siekierce ustalone dla okresu 1963–2010

Analyzing the specific discharges shown in Table 2, one can find out that there is an important difference in characteristic of the two rivers, i.e. higher values in the Zwoleńka of low flow: Q_{90}, Q_{95}, Q_{99} and $Q_{99,5}$ i.e.

higher in the range of 40–68% than in Zagożdżonka, and lower values for discharges with short time of exceedance i.e. Q_{10}, Q_5, Q_1 and $Q_{0,5}$.

Apart from the difference in catchment area, the two catchments have various ratio of afforestation (i.e. 0.41 and 0.24 in Zagożdżonka and Zwoleńka, respectively), various shape factor defined as the drainage area divided by the square of the main channel length (0.60 and 0.29), different mean slope of the river channel (0.0024 and 0.0016) as well as shape and soils of their valleys, which in case of the Zwoleńka River is significantly wider (up to 500 m) and is characterized by mainly organic soils (see Table 1).

Table 2. Selected ordinates of FDCs of the Zagożdżonka River and the Zwoleńka River for the period 1963–2010
Tabela 2. Wybrane rzędne krzywej sum czasów trwania rzeki Zagożdżonki i Zwoleńki dla okresu 1963–2010

Percentage of time the flow is exceeded	Daily flow from the catchment (m^3/s)		Specific discharge ($dm^3/s/km^2$)		Ratio of specific discharges of the Zwoleńka vs Zagożdżonka
	Zagożdżonka	Zwoleńka	Zagożdżonka	Zwoleńka	
1	2	3	4	5	6
0.5	2.221	3.529	27.0	18.9	0.70
1	1.678	2.830	20.4	15.1	0.74
5	0.696	1.415	8.45	7.57	0.90
10	0.492	1.076	5.97	5.76	0.96
20	0.346	0.815	4.20	4.37	1.04
50	0.196	0.520	2.38	2.79	1.17
80	0.116	0.345	1.41	1.85	1.31
90	0.086	0.272	1.04	1.46	1.40
95	0.069	0.229	0.84	1.23	1.46
99	0.042	0.155	0.51	0.83	1.63
99.5	0.036	0.137	0.44	0.73	1.68
Mean value	**0.277**	**0.643**	**3.36**	**3.44**	**1.03**

Higher retention i.e. higher low specific discharge and lower flood once, is typical for larger catchments. In this case however, there

might have been also other more influential reasons of the difference in the shape of FDCs as:

- large forest areas in the Zagożdżonka catchment (40%), consuming water for evapotranspiration, are decreasing the dry period discharge,
- meandering channel in a wide valley of organic soils, lower river channel slope and elongated shape (lower shape factor) of the Zwoleńka catchment are the factors, which reduce the high flow discharges.

4. Conclusions

Results of long term hydrological investigation have delivered very valuable information about variability of renewable water resources. The 48-year investigation carried out in a small agricultural catchment of the Zagożdżonka River located in centre of Poland, characterized by mean precipitation of 611 mm/a and average runoff of 106 mm/a, are source of hydrological information (as donor catchment) for assessing water resources in other partially gauged catchments.

Three-year hydrological investigation and monitoring in two catchments, Zagożdżonka and Zwoleńka, allowed to establish the flow duration curves for both catchments and to indicate factors influencing differences in the FDCs.

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Krzywe sum czasów trwania przepływów dwóch małych zlewni o różnym okresie obserwacji w nizinnej części Polski

Streszczenie

Krzywa sum czasów trwania przepływów wraz z wyższymi (FDC) przedstawia okres trwania, wyrażony w dniach lub procentach okresu rocznego, danego i wyższych przepływów historycznych w analizowanym profilu rzecznym. Krzywe te są powszechnie wykorzystywane w badaniach hydrologicznych i zasosowaniach hydrotechnicznych dotyczących wyznaczania zasobów energetycznych rzek, planowania i projektowania systemów irygacyjnych, prognoz okresów posusznych, wyznaczania okresowych ładunków zanieczyszczeń, wydatku rumowiska rzecznego czy zamulania zbiorników wodnych. Celem prezentowanych badań było określenie takich krzywych dla dwóch profili recznych małych zlewni rolniczych, zlokalizowanych w południowej części Mazowsza, różniących się długością okresu obserwacyjnego. Rejestracja stanów i pomiary hydrometryczne umożliwiające wyznaczenie dobowych wartości przepływów, w jednym z tych profili (zlewni analoga) obejmują okres 48 lat hydrologicznych, natomiast w drugim profilu (zlewni o krótko-okresowych badaniach) okres 2,5 lat. Wyniki badań wykazały zbieżność średniego rocznego odpływu jednostkowego w analizowanych zlewniach, wynoszacego odpowiednio 3,36 and 3,44 $dm^3/s/km^2$, i różnice w zakresie odpływów jednostkowych okresów posusznych oraz mokrych (tj. o wysokim i odpowiednio niskim prawdopodobieństwie przewyższenia). Wskazano na różnicę we wskźniku lesistości i w parametrach charakteryzujących retencje dolinowe analizowanych zlewni, jako na możliwe przyczyny różnic w ww. odpływach jednostkowych niskich i wysokich.