

SEASONALITY OF MEDIAN MONTHLY DISCHARGE IN SELECTED CARPATHIAN RIVERS OF THE UPPER VISTULA BASIN

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Abstract: The study evaluated seasonality of median monthly discharge in selected carpathian rivers of the upper Vistula basin, namely the Kamienica Nawojowska – Łabowa profile, the Rudawa – Balice profile, and the San – Przemyśl profile. To this end, Colwell's indices, analysis of autocorrelation and spectral analysis were used. The data for calculations, i.e. a series of observations of daily discharge from the multi-annual period of 1983-2012, were obtained from the Institute of Meteorology and Water Management – National Research Institute in Warsaw. The study showed no regular seasonality of median monthly discharge in the analyzed rivers. This was evidenced by the value of Colwell's indices, with contingency M accounting for less than 50% of predictability P in the hydrological regime of the studied rivers. This conclusion was also confirmed by statistically significant results of the autocorrelation analysis and results obtained from the spectral analysis. The study indicated that Colwell's indices may be a simple and effective tool for evaluating seasonality of discharge in rivers of the southern Poland.

Key words: Colwell's indices, hydrological regime, seasonality of discharge

1. INTRODUCTION

Seasonal variability of the outflow from the Polish rivers is clear and it depends on precipitation and air temperature. Thus, variability of hydrometeorological conditions significantly affects the hydrological regime of watercourses and seasonality of their discharge (Piętka, 2009; Stanisławczyk & Tomalski, 2015). River catchments are characterized by differing degrees of seasonality, depending on the period of occurrence, volume, frequency and duration of precipitation and the river outflow per se (Carey et al., 2010; Torres et al., 2011; Onyutha, 2016). Hence, seasonality is defined as the expected oscillations in the studied time series that recur every hydrological year (Ali et al., 2013). Also the climate change influence on seasonality of hydrological regime and trends of its elements (Banasik & Hejduk, 2011; Ahmad et al., 2015; Dong et al., 2015, Emam et al., 2015, Mujere & Eslamian 2014; Wijngaard et al., 2016).

Seasonality belongs also to the most important hydrological information, as not only is it a feature of the river system, but it also allows for an appropriate

control of water management activities in relation to water resources of a catchment. In addition, it represents an essential hydrological feature allowing for the classification of catchment areas or their regionalization (Parajaka et al., 2009; Olden et al., 2012; Bardsley, 2016, Berhanu et al., 2015).

Currently, there are many methods used for determination of seasonality of the river outflow in Poland. Their selection depends on such factors as the scope of the studied event or availability of hydrometric information. The commonly used methods include: hydrological periods method (Rotnicka, 1977), outflow concentration and seasonality index (Jokiel & Bartnik, 2001) and measurements of hydrological system stability and river outflow variability (Wrzesiński, 2013).

With regard to other methods used internationally to study seasonality, one should mention the so-called approach of quantifying degree of seasonality based on statistical indices, e.g. the Pardé coefficient (Pardé, 1947). Another method, proposed by Laaha & Blöschl (2006), is based on the so-called seasonal histograms, used to determine monthly distribution of low discharge. Other methods

of studying the seasonality of hydrological regimes refer to a predefined threshold discharge, e.g. marginal or zero discharge. The discharge is selected arbitrarily, depending on parameters of the hydrological regime under study (Poff, 1996; Young, 1999; Robertson et al., 2013). Seasonality of hydrological phenomena may be also analyzed by the method of time series decomposition. It allows for identifying cyclic components of a spectrum of time series – i.e. trend, seasonality (cyclicality) and randomness (Churakova et al., 2014; Azad & Rajeevan, 2016). To assess seasonality of river hydrological regime, the so-called Colwell's indices (or modifications thereof) are used. For the purpose of this method, seasonality is described by the index of predictability (P) and its components, i.e. constancy (C) and contingency (M) (Kennard et al., 2010). Colwell's indices are also used to assess reproducibility of other hydrological phenomena, e.g. diversity of discharge velocity (Riddell & Leggett, 1981), distribution of precipitation throughout the year (Miller, 1984), or classification of discharge regime (Webb et al., 2012; Zhang et al., 2012), and seasonality of low discharge (Wałęga & Młyński, 2016).

Since seasonality, predictability and stability of river hydrological regime, as well as the variability of available resources related thereto, are important both from the scientific and economic point of view, the aim of this study was to evaluate median monthly discharge (MMF) in selected rivers of the upper Vistula basin, using Colwell's indices. This method is not commonly used or recognized in Poland, and therefore the feasibility of its application in the catchment areas in the southern Poland was investigated. The results were additionally compared with values acquired from the autocorrelation analysis and spectral analysis. The study should help to verify whether seasonality of discharge, as calculated thorough Colwell's indices, is determined in a correct manner. Should the results be positive, this method may provide an alternative to other, more advanced methods for detection of seasonality.

2. DESCRIPTION OF THE STUDY AREA

The study covered three elementary carpathian catchments of the upper Vistula basin: the Kamienica Nawojowska – Łabowa cross-section, the Rudawa – Balice cross-section, and the San – Przemyśl cross-section (Fig. 1). The main assumption of selected criteria catchments were natural discharge conditions, without anthropogenic hydrological interventions. Thus, this catchment can be regarded as a natural. The Kamienica Nawojowska is a right tributary of the

Dunajec and it is located in the south-eastern part of the Małopolska Province. Its area up to Łabowa cross-section is 64.9 km². The catchment is covered mainly by forests (76.4%). Arable lands take up 23.2% and the rest (0.4%) is an anthropogenic area. The Kamienica Nawojowska springs in the southern part of the Jaworzyna Krynicka massif. This river marks the border between geographical regions of the Low Beskid and Beskid Sądecki. The Kamienica Nawojowska is a meltwater river, with typical mountain features, such as the occurrence of sudden surges after heavy rains. In abiotic terms it is a flysch stream of type 12. The Rudawa is a left tributary of the Vistula and it is located in the north-western part of the Małopolska Province, within Kraków District.

Its catchment area down to Balice cross-section is 289 km². Most of the catchment area is covered by arable lands (65.0%). A large part (26.6%) is covered by forests, dominated by deciduous species. The rest (8.4%) is an anthropogenic area. From its source down to the Raclawka tributary, the Rudawa is an upland carbonate river with coarse-grained substrate (abiotic type 7) that is further transformed into a small upland river of type 9. The San is a right tributary of the Vistula and it extends over an area of several districts of the Podkarpackie Province. It springs from the western part of the Bieszczady Mountains (Ukraine). Its catchment area down to Przemyśl cross-section is 3.686 km². The land use of catchment area is following: 45.0% arable lands, 35.0% forests, 16.0% pastures and 4.0% fallow lands. In abiotic terms the San from the source to the Wołosaty stream is a flysch river of type 12, then at the cross-section until Solina reservoir is a small flysch river (type 14), and it reaches the gauged cross-section as a mid-size eastern upland river of type 15 (Wałęga et al., 2016).

3. MATERIALS AND METHODS

The data needed for the analysis, i.e. a series of observations of daily discharge (Q_d) from the multi-annual period of 1983-2012 (30 years), had been obtained from the Institute of Meteorology and Water Management, National Research Institute in Warsaw. Based on the obtained hydrometric data, indices for average discharge and Colwell's indices for monthly median discharge (MMF) were determined. The study was supplemented with autocorrelation analysis of MMF discharge.

3.1. Indices for average discharge

The hydrometric data were used for determination of the following indices for average discharge in the studied catchments (Chowdhury &

LEGEND:

- ▼ cross-sections (1 - Łabowa; 2 - Balice; 3 - Przemyśl)
- rivers
- Vistula basin from Przemsza to Nida
- Soła basin
- Skawa basin
- Raba basin
- Dunajec basin
- Nida basin
- Vistula basin from Nida to Wisłoka
- Wisłoka basin
- Vistula basin from Wisłok to San
- San basin to Wisłok
- Wisłok basin
- San basin from Wisłok to estuary
- Vistula basin from San to Sanny
- water region of Dniestr
- water region of Orawa

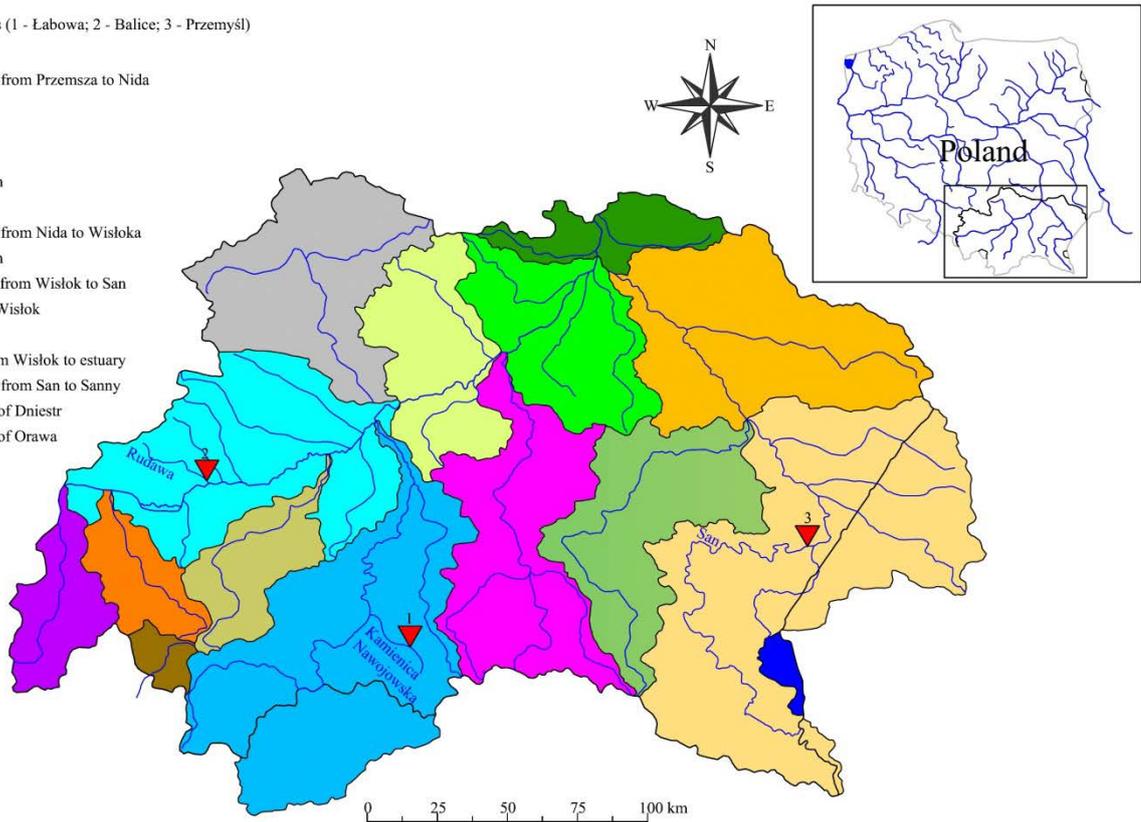


Figure 1. Location of gauge profiles in the studied catchments of the upper Vistula basin

Eslamian 2014): average unit runoff for the multi-annual period (q_{AF}), median daily discharge (M_{Qd}), coefficient of variation of daily discharge (CV_{Qd}), coefficient of skewness of daily discharge (Ske_{Qd}), coefficient of variation of average monthly discharge (CV_{MAF}), average annual unit runoff from the investigated catchments (q_{MAR}), coefficient of skewness of average annual unit runoffs (Ske_{MAR}), kurtosis of average annual unit runoffs ($Kurt_{MAR}$), and median average annual unit runoff (M_{MAR}).

3.2. Colwell's indices

The following Colwell's indices were determined for median monthly discharge: predictability P and its two components: constancy C and contingency M . The P value represents a measure of confidence with regard to the state of an event at a given point. The index of constancy C describes the tendency of a variable to remain unchanged for a given period of time. Contingency M determines the degree of reproducibility of events, and if they occur in annual cycles, this index becomes the measure of seasonality. Colwell's indices scale between 0 and 1. Constancy C takes on the maximum value ($C = 1$) if the analyzed variable has the same value for all the investigated periods. The index of contingency M takes on the maximum value ($M = 1$) when the value

of the variable is different in successive time steps but the occurrence of given values is predictable. Predictability is a measure of regularity of occurrence of the analyzed event. When P exceeds 50%, the regularity of occurrence of the event is above average; when it is less than 50%, the regularity of the event is below average. The measure of seasonality of the studied event is index M . When it represents at least 50% of predictability, seasonality is regular; when contingency is less than 50%, seasonality is irregular (Colwell, 1974).

Colwell's indices are determined based on frequency matrices of the studied event, where columns describe the studied periods of its occurrence and rows show states of the event. The values of states are most often described by means of class intervals whose number is selected intuitively. In this work, the boundaries between class intervals were determined by the following equations (Milhous, 2012):

$$B = \alpha \cdot C_1 \cdot AF \quad (1)$$

where:

α – number of a successive interval,

AF – average discharge in the multi-annual period, expressed in $m^3 \cdot s^{-1}$,

C_1 – value determined by the following formula:

$$C_1 = \frac{4,4}{n-1} \quad (2)$$

where:

n – number of adopted intervals.

In this paper, 12 class intervals were adopted for the analysis of Colwell's indices.

For the frequency matrix with the number of columns t and rows (intervals) s , N_{ij} is the number of years in which the event occurred in the state i and time j . Next, the sum of columns (X_j), rows (Y_i) and the total amount (Z) can be calculated as (Stearns 1981):

$$X_j = \sum_{i=1}^s N_{ij} \quad (3)$$

$$Y_i = \sum_{j=1}^t N_{ij} \quad (4)$$

$$Z = \sum_i \sum_j N_{ij} = \sum_j X_j = \sum_i Y_i \quad (5)$$

The uncertainty with regard to time ($H(X)$), state ($H(Y)$) and the interaction of time and state ($H(XY)$) can be calculated as:

$$H(X) = - \sum_{j=1}^t \frac{X_j}{Z} \log \frac{X_j}{Z} \quad (6)$$

$$H(Y) = - \sum_{i=1}^s \frac{Y_i}{Z} \log \frac{Y_i}{Z} \quad (7)$$

$$H(XY) = - \sum_i \sum_j \frac{N_{ij}}{Z} \log \frac{N_{ij}}{Z} \quad (8)$$

The conditional uncertainty ($H_X(Y)$) as to the state (in the same time) can be defined as:

$$H_X(Y) = H(XY) - H(X) \quad (9)$$

Colwell's indices range between 0 and 1 and are determined according to the below formula:

$$P = 1 - \frac{H_X(Y)}{\log(s)} = 1 - \frac{H(XY) - H(X)}{\log(s)} \quad (10)$$

$$C = 1 - \frac{H(Y)}{\log(s)} \quad (11)$$

$$M = \frac{H(X) + H(Y) - H(XY)}{\log(s)} \quad (12)$$

$$P = C + M \quad (13)$$

In this work, Colwell's indices were determined for twelve one-month periods in chronological order of a hydrological year (November to October). The monthly periods the water discharge were considered because in case when rivers are characterized by the seasonal that in monthly periods it is clearly visible. Moreover in this periods can see the potential changes in the hydrological regime. In addition, the authors determined the effect of the length of an observation series (respectively 10, 20 and 30 years) and the adopted number of class intervals (8, 10, 12, 14, 16 class intervals) on the values of individual indices.

3.3. Analysis of autocorrelation

In order to describe the time variability of

sequences of median monthly discharge, the autocorrelation analysis was performed so as to investigate delayed correlation between variables (Wałęga & Michalec, 2014). The values of the delayed correlation coefficient are determined by the following formula:

$$r_m = \frac{\sum_{n=1}^N [(x_n - \bar{x})(x_{n-m} - \bar{x})]}{\sum_{n=1}^N (x_n - \bar{x})^2} \quad (14)$$

where:

m – delay,

n – number of observations,

x – successive observations,

x_{n-m} – successive observations delayed by m ,

\bar{x} – average value for observations (no delay).

Statistical significance of the correlation coefficients was determined based on the Q Ljung-Box test. A null hypothesis was put forward, stating that the autocorrelation coefficients were not statistically significant, as compared to an alternative stating that individual values of the sequence significantly correlated with one another. The studied hypotheses were verified at the significance level of $\alpha = 0.05$. The Box-Ljung statistic takes the following form (Ljung & Box, 1978):

$$Q = n(n+2) \sum_{i=1}^k \frac{r_{m_i}^2}{n-1} \quad (15)$$

where:

Q –Ljung-Box test statistic,

n – number of observations,

k – autocorrelation shift,

r_{m_i} - autocorrelation coefficient for shift $k = 1$.

The tested null hypothesis indicated that distribution of observations in the sample was independent (no autocorrelation). In the case of a large number of observations, the Q statistic has distribution χ^2 with k degrees of freedom. When for the assumed significance level α , the determined values of statistic Q are greater than or equal to the critical value $\chi^2_{kr(k)}$, the null hypothesis is rejected, which indicates the autocorrelation of the studied time series.

3.4. Time series periodicity

Periodicity of median monthly discharge time series in catchments of the analyzed rivers was assessed using a spectral analysis designed to investigate the harmonic structure of time series. The aim of the analysis is to break down a complex time series containing cyclical elements into a few basic sinusoidal functions (sine and cosine) with specific wavelengths. This analysis allows for discovering a few periodic cycles of variable length that at first appeared to be more or less random

noise. A general model of the spectral function might be described with multiple regression function (Conrad & Pollak, 1950; Elliott & Rao, 1982; Haan, 2002)

$$X_t = a_0 + \sum [a_k \cdot \cos(\lambda_k \cdot t) + b_k \cdot \sin(\lambda_k \cdot t)] \quad (16)$$

where:

X_t – value of a random variable at t time,

a_0 – free term,

a_k and b_k – regression coefficients,

λ_k – frequency,

t – time.

4. STUDY RESULTS

4.1. Indices for average discharge

Based on the hydrometric data obtained in the form of daily discharge during the the multi-annual period of 1983-2012, the following values were determined: average monthly discharge (Figs 2-4), average discharge indices (Table 1), and course of changes in the specific runoff for each month, for the Kamienica Nawojowska, the Rudawa and the San.

The results presented in Table 1 indicated that the Kamienica and the San are rivers with the mountain hydrological regime, while Rudawa is an upland river. This is evidenced by values of q_{SSQ} , i.e. respectively: 17.71; 14.54 and 7.26 $\text{dm}^3 \cdot \text{s}^{-1} \cdot \text{km}^{-2}$. The differences in the runoff resulted from an increase in average specific runoff from mountainous areas, with increasing altitude and changes in the geological structure that reduce permeability of the ground (Wałęga et al., 2015). As far as the variation coefficients determined for daily discharge were concerned, it is notable that, according to Mucha's classification (1994), the discharge in the studied mountain rivers were characterized by very high and extremely high variation. At the same time, the dynamics of changes in the Rudawa's daily discharge remained at a high level. Also, the coefficient of variation determined

for the average annual runoff from the studied catchments gave an indication of high variability of these values. Analysis of the coefficients of skewness, determined for daily discharge and annual runoff, demonstrated that these variables had a right-sided asymmetry of distribution. Thus, within the studied multi-annual period, both the daily discharge and annual runoff were most often below the average discharge in the multi-annual period and the average annual runoff. In addition, the analysis of kurtosis determined for the annual runoff during the multi-annual period of 1983-2012 showed that these variables were characterized by a leptokurtic distribution, which indicated that many of the observations were similar to one another, and the number of variables that significantly deviated from the average value was irrelevant. An analysis of the median monthly discharge showed that for the Kamienica Nawojowska (Fig. 2) and the Rudawa (Fig. 3) the highest values were observed in July and the lowest in January for Kamienica Nawojowska and August for Rudawa. For the San (Fig. 4), the highest median monthly discharge was determined for April and the lowest for August. In addition, it was found that, throughout a year, the studied mountain rivers (Kamienica and San) were characterized by a varying course of average monthly discharge. Floods in individual months alternated with low water periods. This results from the rapid runoff of rainwater or meltwater caused by poor retention capacity of the catchment area (Wałęga et al., 2015). In the catchment of the Rudawa, an upland river with a high retention capacity, even incidental strong rain does not cause floods. High retention capacity of the Rudawa catchment favors more regular annual outflow as compared to the mountain catchments. This was confirmed by the values of the runoff coefficients: 0.55 for the Rudawa, and 0.88 for the Kamienica Nawojowska and the San (Czarnecka 1976).

Table 1. Average discharge indices for the studied rivers of the upper Vistula basin

| River | Parameter | | | | | | | | |
|-----------|--|----------------------------------|-----------|------------|------------|---|-------------|--------------|---|
| | q_{SSQ} | M_{Qd} | CV_{Qd} | Ske_{Qd} | CV_{MAF} | q_{MAR} | Ske_{MAR} | $Kurt_{MAR}$ | M_{MAR} |
| | $\text{dm}^3 \cdot \text{s}^{-1} \cdot \text{km}^{-2}$ | $\text{m}^3 \cdot \text{s}^{-1}$ | - | - | - | $\text{m}^3 \cdot \text{r}^{-1} \cdot \text{km}^{-2}$ | - | - | $\text{m}^3 \cdot \text{r}^{-1} \cdot \text{km}^{-2}$ |
| Kamienica | 17.71 | 16.41 | 2.18 | 12.98 | 0.87 | 6.47 | 1.19 | 2.01 | 6.13 |
| Rudawa | 7.26 | 6.02 | 0.76 | 7.38 | 0.47 | 2.65 | 1.02 | 1.03 | 2.44 |
| San | 14.54 | 10.42 | 1.02 | 5.21 | 0.63 | 5.31 | 0.61 | 0.45 | 5.19 |

Note: q_{SSQ} – average specific runoff for the multi-annual period; M_{Qd} – median daily discharge; CV_{Qd} – coefficient of variation of daily discharge; Ske_{Qd} – coefficient of skewness of daily discharge; CV_{MAF} – coefficient of variation of average monthly discharge; q_{MAR} – average annual specific runoff from the investigated catchments; Ske_{MAR} – coefficient of skewness of average annual specific runoff; $Kurt_{MAR}$ – kurtosis of average annual specific runoff; M_{MAR} – median average annual specific runoff

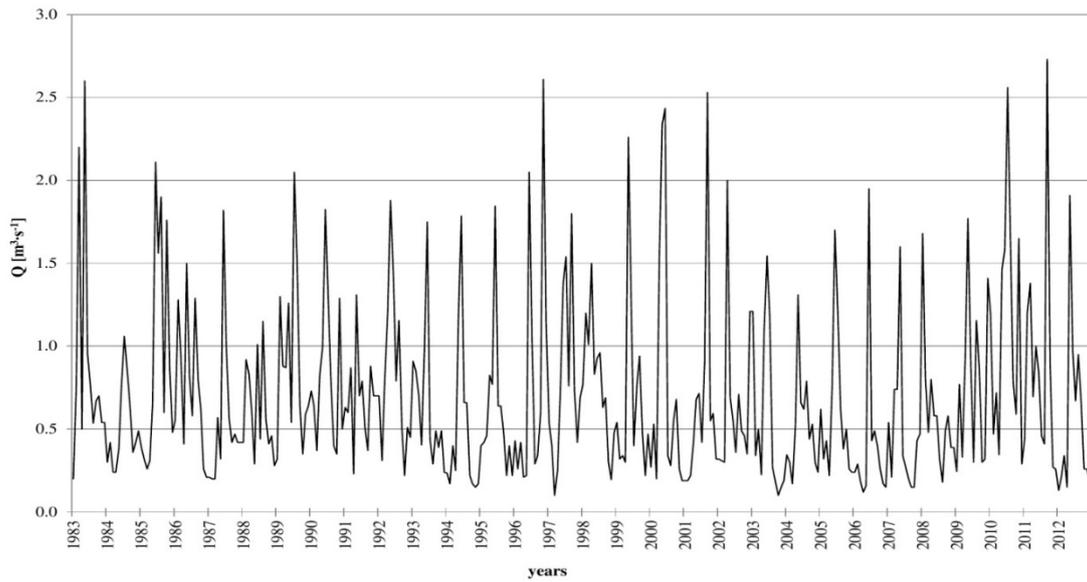


Figure 2. Course of median monthly discharge for the Kamienica Nawojowska

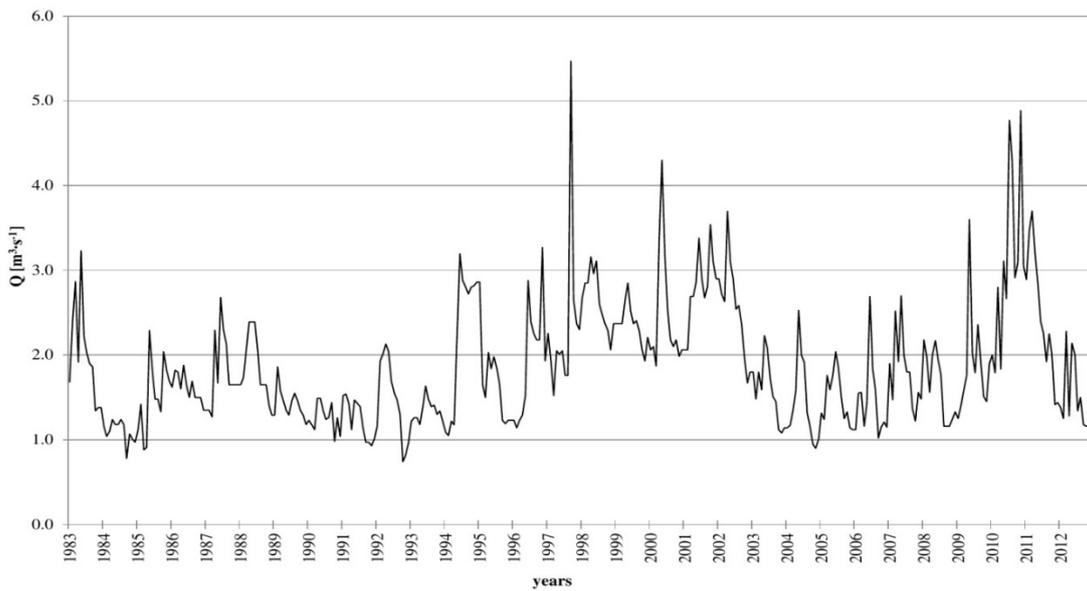


Figure 3. Course of median monthly discharge for the Rudawa

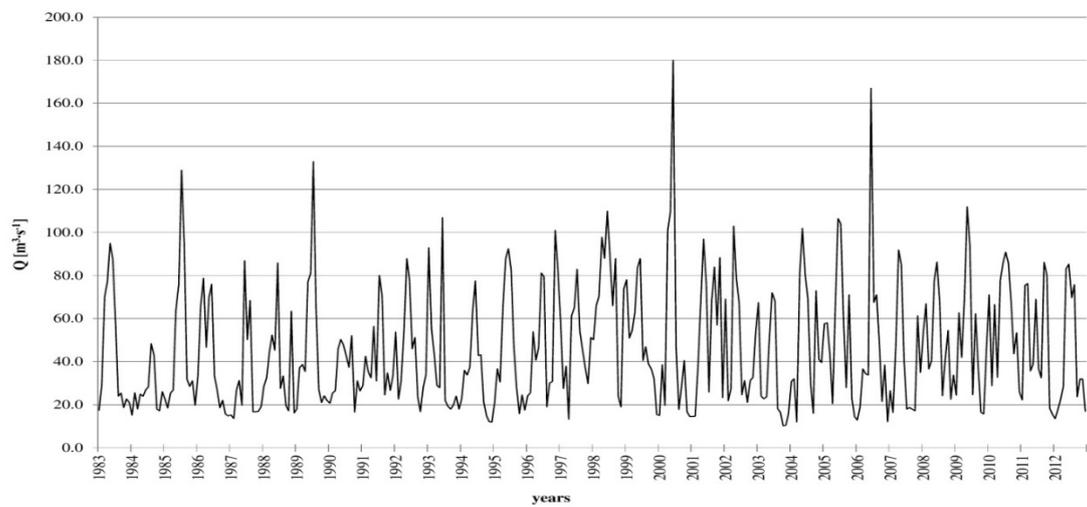


Figure 4. Course of median monthly discharge for the San

4.2. Colwell's indices

The hydrometric data were used to determine Colwell's indices: predictability P and its components, i.e. constancy C and contingency M for median monthly discharge in the carpathian rivers: Kamienica – Łabowa cross-section, the Rudawa – Balice cross-section, and the San – Przemyśl cross-section. The results of the calculations are presented in Table 2.

The results summarized in Table 2 indicated that the studied mountain rivers, the Kamienica and the San, were characterized by predictability below 50%, meaning that the predictability of their hydrological regime was below average. As for Rudawa, the determined P value indicated that the predictability of the studied discharge exceeded the average level. Thus, Rudawa's median monthly discharge can be forecast in a relatively easy manner. What is more, this river was proven to have the highest index C, indicating high stability of monthly discharge. An analysis of contingency M, as determined for the studied rivers, demonstrated that for all of them the index constituted less than 50% of the predictability and hence the median monthly discharge was only slightly determined by individual seasons of a hydrological year.

Table 2. Colwell's indices for MAF discharge in the analyzed river catchments

| River | Colwell's indices | | | | |
|-----------|-------------------|------|------|------|------|
| | P | C | M | C/P | M/P |
| Kamienica | 0.28 | 0.17 | 0.11 | 0.63 | 0.30 |
| Rudawa | 0.51 | 0.46 | 0.05 | 0.91 | 0.09 |
| San | 0.38 | 0.27 | 0.11 | 0.70 | 0.30 |

The analysis of seasonality based on Colwell's indices was supplemented by an analysis of the effect of the length of the observation series and the assumed number of class intervals on the values of individual indices. The results are presented in figures 5 and 6 respectively.

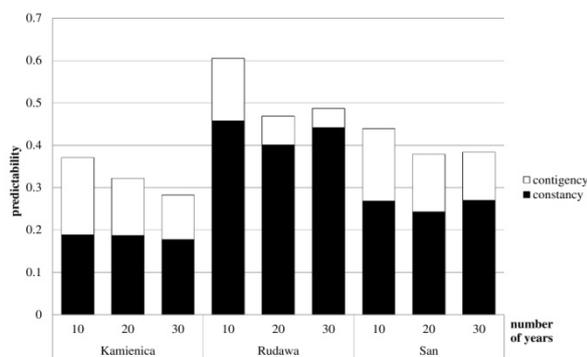


Figure 5. Effect of the length of the observation series on the values of Colwell's indices

A scrutiny of the results presented in figure 5 showed that the highest predictability for median monthly discharge in the studied rivers was achieved for a multi-annual period of 10 years. As the index of P represents the regularity of occurrence of the studied phenomenon, it can be concluded that an increase in its value, accompanied by a shortening of an observation series, resulted from an increased likelihood of covering the years with similar runoff values (i.e. years with regular runoff) with shorter observation series, rather than longer sequences (which can cover both dry and wet years). These results confirm analyses carried out by other authors. In their work, Gan et al., (1991) demonstrated a strong negative curved relationship between predictability and the length of the observation series. They also found that the length of the observation series significantly affected contingency. On the other hand, constancy was independent of the number of years in the multi-annual period. It should also be noted that reducing the length of an observation series increased the M/P ratio that determines the regularity of seasonality of median monthly discharge. Nevertheless, one may assume that these differences were not significant, as for each of the analyzed rivers, the M/P ratio remained below 50%, regardless of the length of the series.

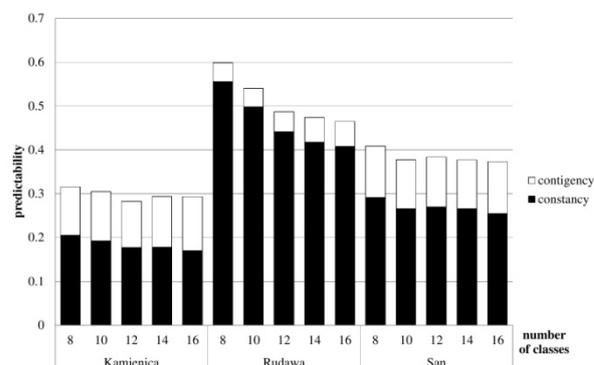


Figure 6. Effect of the number of class intervals on the values of Colwell's indices

The data presented in figure 6 demonstrated that predictability depended on the number of class intervals. A decrease in the number of class intervals was accompanied by an upward trend in P. Nonetheless, it should be noted that these differences were small. Disparities for the extremes in P were respectively 11% for the Kamienica, 22% for the Rudawa, and 9% for the San. It should be also noted that with an increasing number of class intervals, the values of C would generally decrease, while index M remained unchanged. Therefore, it caused an increase in the M/P ratio that determined the regularity of seasonality of median monthly discharge.

4.3. Analysis of autocorrelation

In addition to the analysis of seasonality of median monthly discharge, the authors determined the significance of their autocorrelation coefficients. The results are presented in Figures 7-9. Range of trust were established for significant level equals 0.05. Correlation coefficient (CC) were calculated by the (14) formula. Standard error (S. E) is the standard deviation of the sampling distribution of a statistic. Ljung-Box statistics (Q) were calculated by the (15) formula. If calculated probability (p) is higher than assumed significant level, then values of CC are significant.

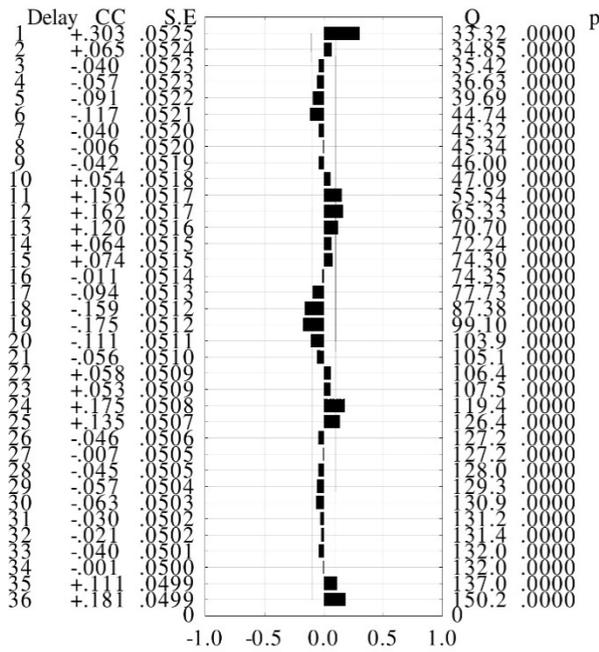


Figure 7. Correlogram of a series of monthly median discharge in the Kamienica Nawojowska, Łabowa profile; — Range of trust; CC - Correlation coefficient; S.E - Standard error; Q - Ljung-Box statistics; p - probability.

The correlograms prepared for the Kamienica Nawojowska and the San (Figs 7 and 9) indicated that the median monthly discharge showed certain, about 12 months seasonality of occurrence. It should be noted, however, that it is not regular. As far as the Rudawa is concerned, the constancy of discharge within a sequence was clear, which made it easy to forecast. This results from the hydrological regime of the studied rivers and their retention capacities. The results presented in Table 2 confirm the above. The lowest M/P ratio was determined for the Rudawa (9%), with 30% for the Kamienica Nawojowska and the San. It should be noted, however, that the values resulting from the autocorrelation analysis indicated a strong internal correlation between monthly median discharge. For each of the analyzed cases, the test

probability p was below the assumed significance level $\alpha = 0.05$. Thus, the autocorrelation coefficients are statistically significant. This course of the autocorrelation function proved that this was a non-stationary process. The highest values of the Q Box-Ljung statistic were obtained for the Rudawa, where the determined autocorrelation coefficients took on only positive values.

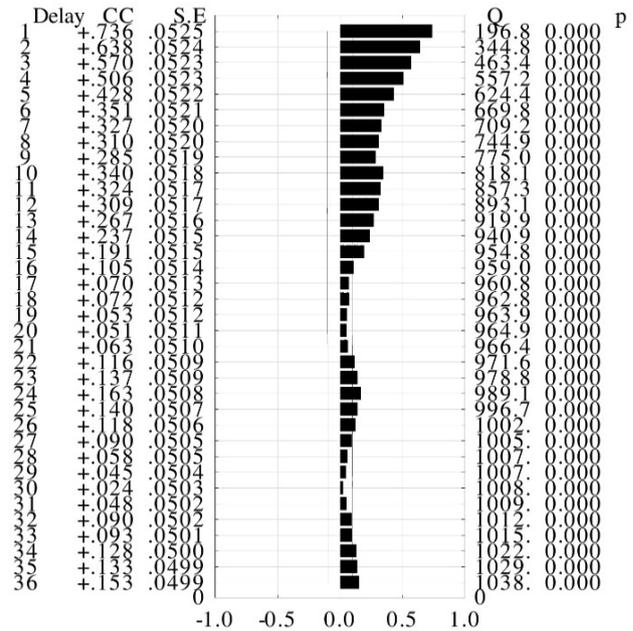


Figure 8. Correlogram of a series of monthly median discharge in the Rudawa, Balice profile; (Explications shown in Fig. 7).

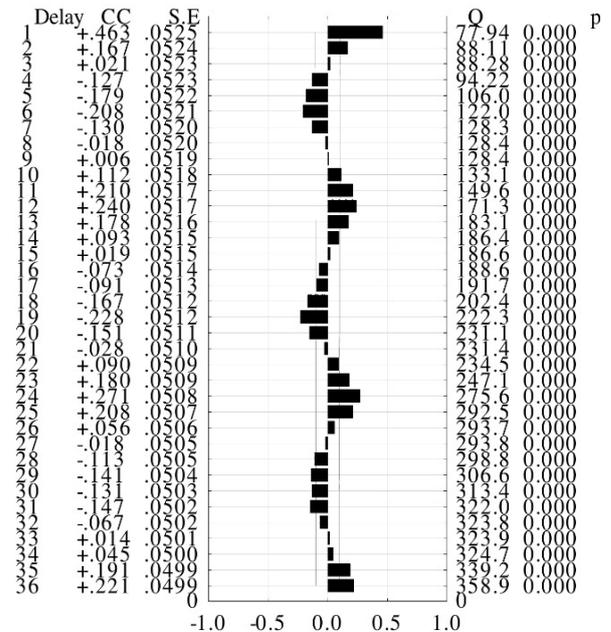


Figure 9. Correlogram of a series of monthly median discharge in the San, Przemyśl profile; (Explications shown in Fig. 7).

4.4 Time series periodicity

Another element investigated of this study was the periodicity of median monthly discharge for the study catchments. This was performed using spectral analysis designed for evaluation of the harmonic structure of time series. The analysis outcomes are presented in figures 10 – 12.

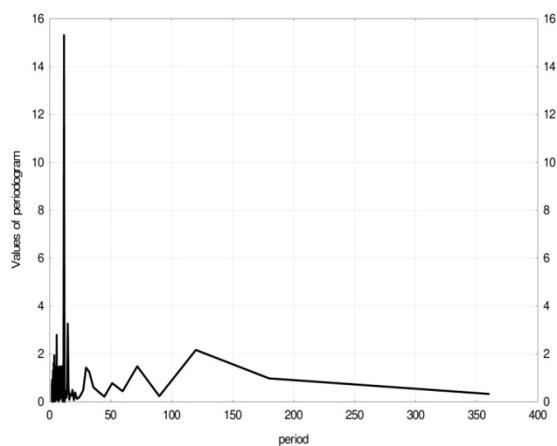


Figure 10. Periodogram of median monthly discharge for the Kamienica Nawojowska catchment

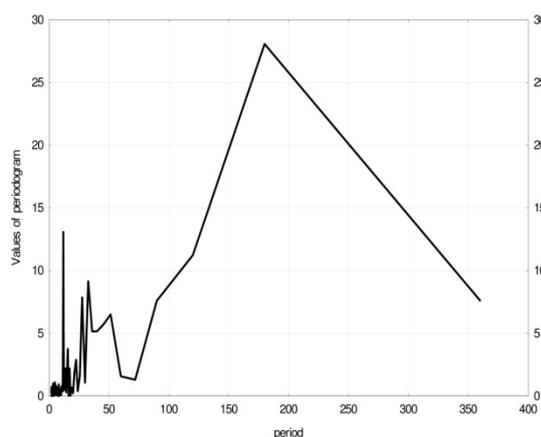


Figure 11. Periodogram of median monthly discharge for the Rudawa catchment

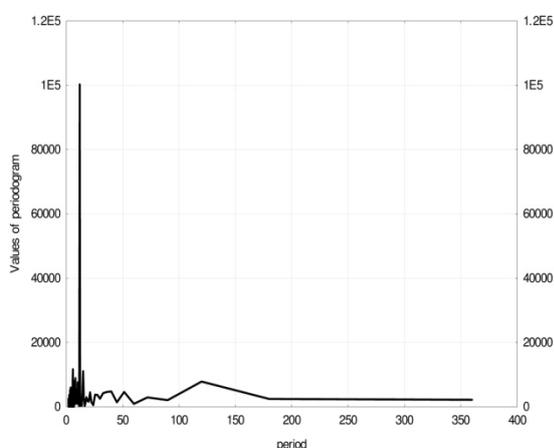


Figure 12. Periodogram of median monthly discharge for the San catchment

An analysis of periodicity of median monthly discharges for the investigated river catchments demonstrated approximately twelve-months cycles for the Kamienica Nawojowska (Fig. 10) and San (Fig. 12). The Kamienica Nawojowska and San are characterized by the mountain regime that may disrupt cycles of the investigated phenomenon. For the Rudawa the periodogram (Fig. 11) has not shown a regular, seasonality. This result are confirmation of Colwell analysis and autocorrelation analysis, which showed some seasonality but irregular of median monthly flow for the Kamienica Nawojowska and San, and showed absence of seasonality for the Rudawa.

5. DISCUSSION

This paper discusses the seasonality of median monthly discharge in the carpathian rivers of upper Vistula basin: Kamienica Nawojowska – Łabowa profile, the Rudawa – Balice profile, and the San – Przemyśl profile. The study was carried out using Colwell's indices, an analysis of autocorrelation and spectral analysis. The results indicated an absence of regular seasonality of median monthly discharge in the studied rivers, which is principally explained by the nature of the rivers' hydrological regime. The analysis included two mountain rivers and one upland river. Mountain watercourses are characterized by high dynamics in terms of changes in discharge intensity. The structure and functioning of these rivers are affected by topography, weather conditions, size and management of the catchment areas, as well as diversified hydrological regime in the upper, middle and lower sections of the watercourses (Strużyński et al., 2015). On the other hand, the absence of seasonality in upland rivers can be explained by large and hardly changeable in time underground runoff, combined with fast flowing water from strong downpours. It should be emphasized that any change in the above factors disturbs the regularity of the discharge, and hence its size, depending on the period of time in which it occurs.

The results of the study presented in this paper are confirmed by other seasonality analyses involving hydrological regimes of rivers located in the upper Vistula basin. In their work, Wałęga & Młyński (2016) evaluated seasonality of low discharge in the Kamienica Nawojowska, based on Colwell's indices. The study showed irregular seasonality of the examined discharge, which was reflected in the average monthly discharge of the river. In another study Pocisk-Karteczka et al., (2010), analyzed spatial diversity and variability of

runoff from mountain catchments, investigating e.g. periodicity of runoff with regard to sequences of annual discharge (harmonic analysis). The study showed no significant periodicity in the values of average annual discharge. Jokieli & Tomalski (2014) analyzed seasonal structure of river runoff in upland and mountain rivers, also located in the upper Vistula basin. Based on the analysis of the mid-term runoff, they demonstrated an absence of seasonality in the runoff from the upland and mountain rivers, which was explained by natural and anthropogenic changes in the seasonal structure of the river runoff from the upper Vistula basin. An analysis of studies on river runoff seasonality in other countries as well as in catchments with other morphologic and climatic conditions indicated that the methodological approach used in this study was an effective tool for the evaluation of the examined phenomenon. This was confirmed by the results presented in the works of Saremi et al., 2011; Fernandez & Sayama 2015; Mohammed et al., (2015), where they studied seasonality of hydrological regime of river catchments (including mountain catchments) located in different climate zones, using Colewell's indices or the autocorrelation analysis.

6. SUMMARY

Seasonality of river discharge is a parameter related to the meteorological characteristics of catchments, and it is directly affected by stability of a hydrological regime. When spring thaws or summer rains take place in the same period of a year, the discharge occurring regularly in the riverbed repeat the rhythm. The study on seasonality of selected rivers in the southern Poland, based on Colwell's indices, autocorrelation analysis and spectral analysis showed no relationship between the size of the median monthly discharge and the periods in which they occur (lack of regular seasonality). It should be emphasized that hydrological regime of rivers is becoming increasingly more complex and more dependent on individual features of the catchment, and human pressure. The results of this work confirm that Colwell's indices can be an effective tool to assess seasonality of hydrological regime of Polish rivers. This is evidenced by consistent results of studies involving the autocorrelation analysis and spectral analysis. Colwell's indices, due to their simplicity, are commonly used to study seasonality of rivers in other countries. It should be noted, however, that in Poland they still need to be appropriately recognized in respect of hydrological events.

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