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EXCEEDANCE PROBABILITY OF SELECTED LOW CHARACTERISTIC FLOWS IN MOUNTAIN CATCHMENTS

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Summary

In Polish hydrology and water management the term *characteristic flow* exists denoting a specific value of flow at the given cross-section of a river calculated as the long-term minimum, mean, median or maximum calculated using the annual minimum, mean, median or maximum flow taken for each year from a series of (usually) daily flows. Some of these characteristic flows are used to define the low-flow (o drought) periods while the another criterion: a percentage flow Q_p taken from the long-term flow duration curve is also widely used.

In the paper the study on the frequency structure the empirical exceedance probability $\hat{P}$ of a given characteristic flow made for some low and average characteristic flows (*SNQ*, *WNQ*, *NSQ* and *SSQ*) is presented. The results show that the exceedance probability of a given characteristic flow is variable, and the amount of this variability may be large, as is the case of *WNQ* and *NSQ*. So assigning a characteristic flow to a single FDC quantile value Q_p (as can be find in the literature) cannot be justified.

Correlation analysis made for the pairs ($\hat{P}$, characteristic flow), ($\hat{P}$, catchment area) and ($\hat{P}$, gauging station elevation) revealed some significant correlations. Only $\hat{P}$ for *SNQ* is not correlated at all; correlation for other characteristic flows is statistically significant for at least one of the cases. The highest correlations (greater than 0.4 in absolute values) were found for the pairs ($\hat{P}$, gauging station elevation) for *NSQ* and, for *SSQ*, ($\hat{P}$, *SSQ*) and ($\hat{P}$, catchment area).

Key words: characteristic flows, flow duration curve, threshold value, *SNQ*, average annual minimum flow, *WNQ*, maximum annual minimum flow, *NSQ*, minimum annual mean flow, *SSQ*, average annual mean flow, Upper Vistula iver

INTRODUCTION

The term *characteristic flow* denotes in Polish hydrology and water management a specific value of flow at the given cross-section of a river calculated as the annual (summer, winter, etc.) minimum, mean, median or maximum flow taken for each year from a series of (usually) daily flows and denoted then *NQ*, *SQ*, *ZQ* or *WQ*, respectively. Such flows are also called characteristic flows of the first kind. By calculating minimum, mean, median or maximum from long-term series of *NQ*, *SQ*, *ZQ* or *WQ* the characteristic flows of the second kind are formed. Only some of the possible 16 characteristic flows of the second kind are of practical value, e.g., *SNQ* (mean annual minimum flow), *WNQ* (maximum annual minimum flow), *SSQ* (average annual mean flow), *NWQ* (minimum annual maximum flow), or *SWQ* (average annual maximum flow).

In defining low flow periods (or hydrological drought) a notion of threshold flow or threshold value is used and many different values of this criterion are applied. Often it is a value of a percentile Q_p read from the flow duration curve (FDC). The value of Q_p is exceeded p% of time of observation, usually 30 years or more. As such, the value of p may be interpreted as the average probability that a given (usually) daily flow is exceeded in an arbitrary year. The adopted value of p in Q_p as threshold value varies according to author and typical values are p = 70%, 90% and 95% (Fleig 2004).

In Poland, apart from certain percentiles Q_p (e.g., $Q_{70\%}$, (Tokarczyk 2010)) which are also common, different characteristic flows are used as the threshold value. Lambor (1971) and Ozga-Zielińska and Brzeziński (1997) define the threshold value as *WNQ* (maximum annual minimum flow). Tokarczyk (2013) recognizes *WNQ* as „the most reasonable hydrological criterion”. Other authors (e.g., Stachý 1990, Farat *et al*. 1995; Mager *et al*. 2000, Tomaszewski 2007) suggest using *SNQ* (average annual minimum flow). Tomaszewski (2011) cites several papers where also another characteristic flow, *ZNQ*, i.e., median annual (or even monthly) minimum flow, is used as the threshold flow.

Unlike quantiles Q_p, all characteristic flows (excluding those whose first letter is *Z*, as in *ZNQ*) are not connected with their exceedance of nonexceedance frequency, so it would be interesting to study such connection. In the literature such information is rather scarce. For example, according to Tokarczyk (2010) $Q_{70\%}$ is approximately equal to *SNQ*, or (Tokarczyk 2008) that $Q_{70\%}$ lies in between *WNQ* and *SNQ*.

The aim of this paper is to study the distribution of exceedance frequency (empirical exceedance probability) of certain characteristic flows: *SNQ*, *WNQ*, *NSQ* and *SSQ*, i.e., the flows not greater than the long-term mean, using many long-term series of daily flows in the area of one catchment.

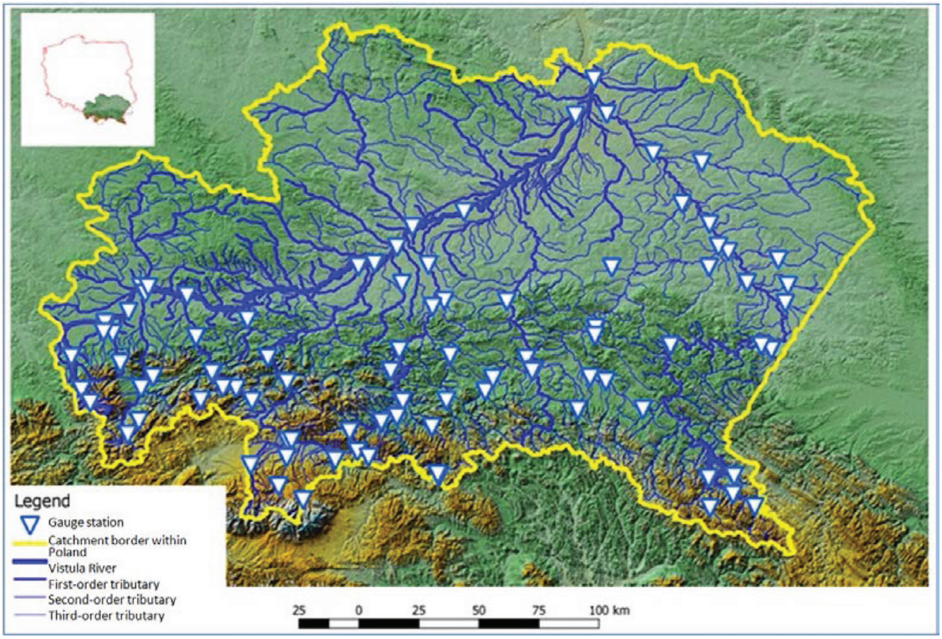

Figure 1. Location of gauging cross-sections in the Carpathian part of the Upper Vistula River basin.

MATERIALS AND METHODS

The area selected covers the Carpathian part of the Upper Vistula River basin (with the Vistula itself) and comprises 90 gauging stations with 30-year (1984-2013) daily flow time series (Figure 1). Each series comprises 10958 daily flows. The gauging cross-sections close catchments of various area ranging from 24.7 km^2 to 50,865 km^2 and the elevation of gauging stations varies from 133 m a.s.l. to 965.6 m a.s.l. The distribution of catchment areas and elevations of gauging stations are shown in Figure 2.

Most gauging station elevations (more than 50 out of 90) do not exceed 300 m a.s.l.; about half of the catchment areas are in between 100 and 1000 km^2.

In Figure 3 a typical flow magnitude in the catchments is presented in the form of the relationship between the average 1984-2013 flow and the catchment area, both in the linear and logarithmic (log-log) scales. As expected, high correlation can be seen in both plots. The correlation coefficient of log-values is 97.3%, in linear scale it equals 99.0%. The plot in the linear scale suggests a slightly nonlinear relation between these variables; the log-log plot suggests it can be a power relationship.

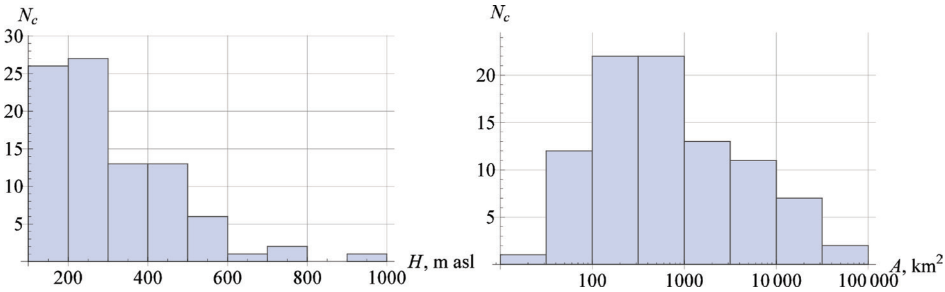

Figure 2. Distribution of number of catchments, N_c, versus gauging station elevation H and catchment area A.

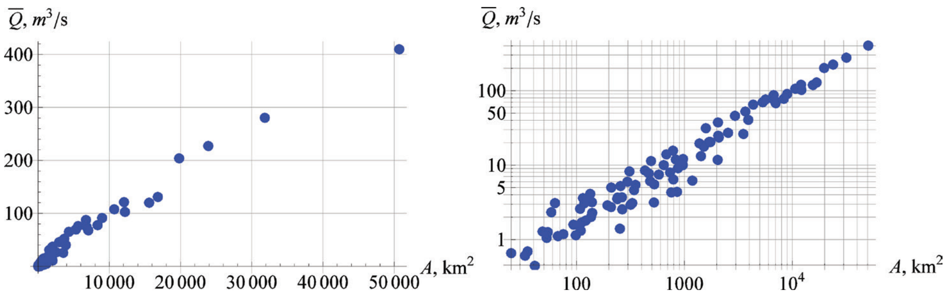

Figure 3. Scattergram of relationship between the average flow and catchment area in the Upper Vistula River catchment in the linear and logarithmic (log-log) scales.

Based on the long-term annual values of minimum flow and annual values of mean flow, four characteristic flows have been selected for each of 90 gauging station, as follows.

(1) average annual minimum flow, *SNQ*

$$SNQ = \frac{1}{n}\sum_{i=1}^{n}\left(\min Q\right)_i \tag{1}$$

(2) maximum annual minimum flow, *WNQ*

$$WNQ = \max_{i=1,\dots,n}\left(\min Q\right)_i \tag{2}$$

(3) minimum annual mean flow, *NSQ*

$$NSQ = \min_{i=1,\dots n}\overline{Q}_i \tag{3}$$

(4) average annual mean flow, *SSQ*

$$SSQ = \frac{1}{n}\sum_{i=1}^{n}\bar{Q}_i \tag{4}$$

Symbol n denotes the length of annual series (n = 30); $(\min Q)_i$ and $\bar{Q}_i$ are minimum and mean flow for the i-th year, respectively.

To calculate empirical exceedance probability for given characteristic flow Q_{char} characteristic the following formula was used:

$$\hat{P}(Q \geq Q_{char}) = \frac{\#\{\mathrm{Q}_i : Q_i \geq Q_{char}\}_{i=1,\ldots,N}}{N} \tag{5}$$

where N is the number of days in the 30-year period (N = 10958) and Q_{char} is one of the characteristic flows *SNQ*, *WNQ*, *NSQ* and *SSQ*.

RESULTS AND DISCUSSION

For each of 90 gauging stations, based on 30-year series of daily flows, characteristic flows defined by equations (1)-(4) have been calculated and, using the period-of-record FDCs, empirical exceedance probability $\hat{P}$ (5) has been assigned to each characteristic flow. The results are shown in Figure 4 and in Table 1.

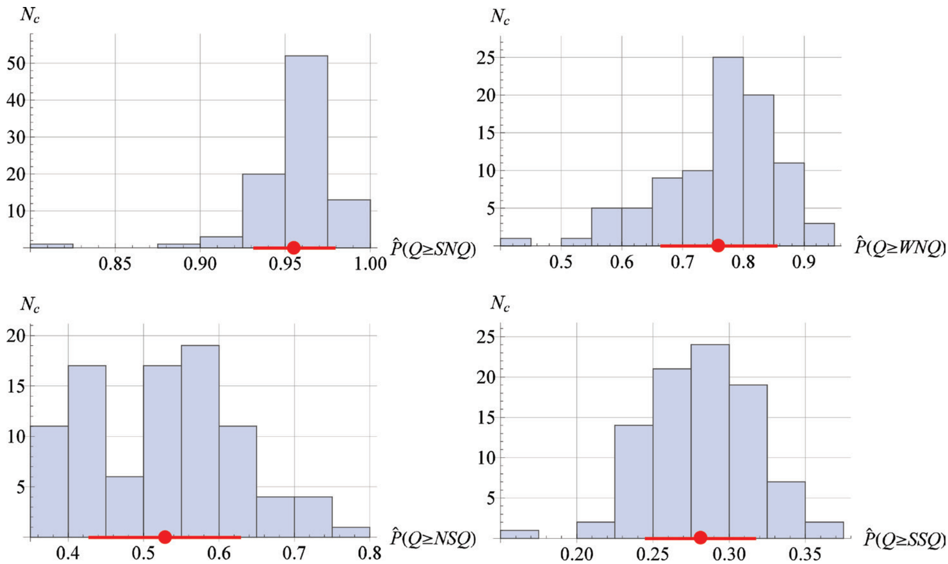

Figure 4. Frequency (expressed as the number of catchments, N_c) distribution of empirical exceedance probability $\hat{P}$, of the selected characteristic flows for the 90 gauging stations. Red point denotes the average exceedance probability, $\bar{\hat{P}}$, red line length is equal two standard deviations $s_{\hat{P}}$ of $\hat{P}$.

Distributions of empirical exceedance probabilities in Figure 4 are unimodal and regular for all characteristic flows with exception of the *NSQ* distributions which is clearly bimodal. The bimodality may suggest the existence of two subpopulations with significantly different properties. First two distributions shows clear negative asymmetry (see Table 1), the last (*SSQ*) is practically symmetrical although its skewness coefficient is slightly negative.

Average values of empirical exceedance probabilities shown in Table 1 allow to approximately assign a quantile Q_p to the characteristic flow: $Q_{95\%}$ to *SNQ*, $Q_{76\%}$ to *WNQ*, $Q_{53\%}$ to *NSQ*, and $Q_{28\%}$ to *SSQ*. This assignment, especially for mean flow *SSQ*, points to the high asymmetry of daily flows, which is characteristic for mountain catchments.

Table 1. Average $\bar{\hat{P}}$ standard deviation $s_{\hat{P}}$ and quartiles $\hat{P}_{25\%}$, $\hat{P}_{50\%}$ and $\hat{P}_{75\%}$ of empirical exceedance probability, $\hat{P}$, of the selected characteristic flows, and their equivalence in number of days per year. Symbol $cs_{\hat{P}}$ denotes the skewness of $\hat{P}$.

Statistic	Characteristic flow							
	SNQ		*WNQ*		*NSQ*		*SSQ*	
	%	days	%	days	%	days	%	days
$\bar{\hat{P}}$	95,3%	348	76,0%	277	52,5%	192	28,0%	102
$s_{\hat{P}}$	2,4%	9	9,4%	34	9,8%	36	3,5%	13
$cs_{\hat{P}}$	-3,1441		-0,8663		0,1747		-0,1421	
$\hat{P}_{25\%}$	94,7%	346	70,5%	257	41,8%	153	25,4%	93
$\hat{P}_{50\%}$	95,4%	348	76,6%	280	53,6%	196	27,7%	101
$\hat{P}_{75\%}$	96,5%	352	82,7%	302	58,5%	214	30,5%	111

The variability of empirical exceedance probabilities, as shown in Table 1, exhibits expected regular behaviour of empirical exceedance probability, i.e., decreasing to the right of Table 1. Different situation is with the standard deviation. The variability of exceedance probabilities for *WNQ* and *NSQ* is quite considerable (more than month, if converted to days). This can be better seen in Figure 6, where all four distributions are sketched comparatively with all three quartiles drawn. The whole variability intervals of *WNQ* and *NSQ* largely overlap; this is to lesser extend true for *SNQ* and *WNQ*. *SSQ* is the only out of the four characteristic flows that practically does not overlap with any other.

It is interesting whether empirical exceedance probability of a characteristic flow is correlated with that flow and/or with the corresponding catchment area *A* and gauging station elevation *H*. The answer is partly yes, partly no. Table 2 shows that in the half of cases this correlation is statistically significant (p-value < 0.01). Exceedance probability $\hat{P}$ of *SNQ* is not correlated at all, $\hat{P}$ for *NSQ* is significantly correlated with all three variables, $\hat{P}$ for *WNQ* is correlated with gauge elevation only, and $\hat{P}$ for *SSQ* is correlated both with *SSQ* and catchment area.

Table 2. Correlation coefficients corr() of empirical exceedance probability, $\hat{P}$,of the selected characteristic flows, Q_{char}, with Q_{char}, catchment area, *A*, and gauging station elevation *H*. The p-values are given for the two-sided test of the zero-correlation coefficient hypothesis.

	characteristic flow, Q_{char}			
	SNQ	*WNQ*	*NSQ*	*SSQ*
corr($\hat{P}$, Q_{char})	0,049	-0,016	**0,251**	**0,460**
p-value	0,324	0,442	**0,008**	**2,58E-06**
corrr($\hat{P}$, *A*)	0,060	0,008	**0,265**	**0,430**
p-value	0,286	0,471	**0,006**	**1,16E-05**
corrr($\hat{P}$, *H*)	0,096	**0,353**	**-0,415**	0,055
p-value	0,183	**0,0003**	**2,43E-05**	0,3028

Statistically significant correlations are in most cases positive, which means, that, for example for *SSQ*, the larger catchment area the larger is the exceedance probability, i.e., the longer is the average duration per year of flows exceeding the *SSQ* value. Statistically significant correlation between $\hat{P}$ and *NSQ* is negative: the higher is the gauging station the shorter is the number of days in a year with flow exceeding *NSQ*.

FINAL REMARKS AND CONCLUSIONS

The study on the frequency structure the empirical exceedance probability $\hat{P}$ of a given characteristic flow made for some low and average characteristic flows (*SNQ*, *WNQ*, *NSQ* and *SSQ*) shows that the exceedance probability of a given characteristic flow is variable, and the amount of this variability may be large, as is the case of *WNQ* and *NSQ*. This finding shows that assigning a characteristic flow to a single FDC quantile value Q_p cannot be justified and, if used, additional relevant information on uncertainty should be given. The average value of $\hat{P}$ for *SSQ* (28%), much less than 50%, shows high asymmetry of catchment flows distribution, which can be explained by the mountain character of most of the catchments.

Correlation analysis made for the pairs ($\hat{P}$, characteristic flow), ($\hat{P}$, catchment area) and ($\hat{P}$, gauging station elevation) revealed some significant correlations. Only $\hat{P}$ for *SNQ* is not correlated at all; correlation for other characteristic flows is statistically significant for at least one of the cases. The highest correlations (greater than 0.4 in absolute values) were found for the pairs ($\hat{P}$, gauging station elevation) for *NSQ* and, for *SSQ*, ($\hat{P}$, *SSQ*) and ($\hat{P}$, catchment area).

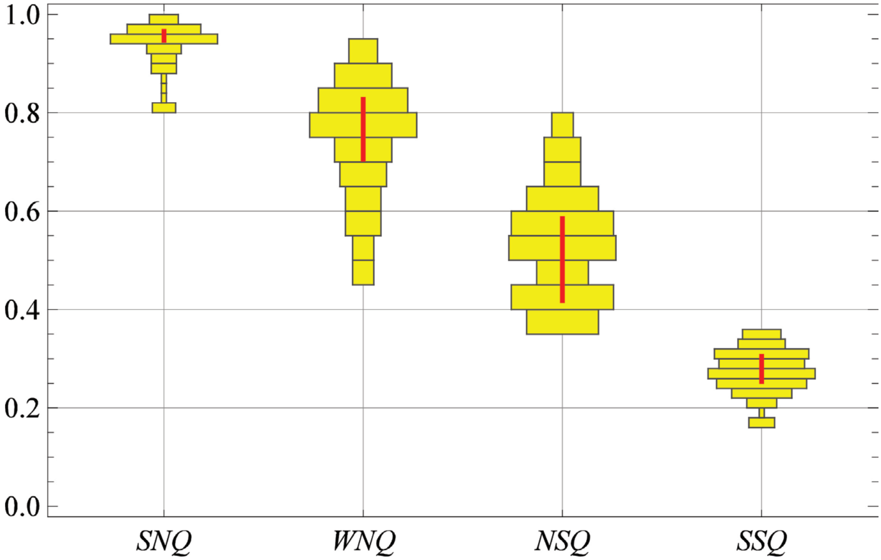

Figure 5. Frequency distribution of empirical exceedance probability, $\hat{P}$,of the selected characteristic flows for the 90 gauging stations. Red point denotes the median exceedance probability $\hat{P}$, red line length is equal to the interquantile distance of $\hat{P}$.

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