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VERIFICATION OF EMPIRICAL FORMULAS FOR CALCULATING MEAN LOW FLOW WITH THE VIEW TO EVALUATING AVAILABLE WATER RESOURCES

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ABSTRACT

Aim of the study
In the present study, we aimed to verify empirical formulas for calculating mean low flow (MLF) with the view to evaluating available water resources for mountain catchments, located in the upper Vistula Basin. The following empirical formulas were analysed: Punzet and Stachý.

Material and methods
The studies were conducted in the following stages: analysis of significant trends for low flows in the analysed catchments, followed by the mean low flows determination using the analysed methods, and the determination of available water resources in relation to MLF obtained from the various analysed methods.

Results and conclusions
The analysis of the results showed lack of statistically significant trends in the course of low flows for the analysed catchments. Also, the analysis indicated significant differences between MLF derived from hydrological data and that derived from empirical formulas. The obtained results indicated the need to update the empirical formulas for calculating MLF, particularly regarding the determination of available water resources in ungauged catchments, in relation to mean low flows.

Keywords: empirical formulas, mean low flow, available water resources

INTRODUCTION

Low flows (*LF*), their course, and their impact on habitat conditions of aquatic ecosystems constitute a significant issue in hydrology and water management. These characteristics are the compound result of complex processes taking place in the catchment area – the processes, which are shaped by physiographic and meteorological conditions. Natural factors affecting the size and the course of *LF* flows include: soil type, infiltration and hydraulic properties, aquifer level, vegetation processes, and evaporation rate (Števková et al., 2012; Cupak, 2017; Cupak et al., 2017). The analysis of low flows, carried out both on an annual and multiannual basis, provides useful information and insight into the nature of water outflow from the catchment, as well as information used to study trends of outflow changes in the aspect of climate change (Kaznowska et al., 2015).

When analysing the use of surface water resources, hydrological calculations should be carried out in order to determine the amount of water available for

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collection, while maintaining the so-called biological balance. Therefore, it is necessary to determine minimum flows (Q_n) or environmental (*EF*) flows, based on the characteristic flows for a given multi-year period (Młyński et al., 2015; Młyński and Wałęga, 2015; Operacz, 2015). The values of Q_n flows form the basis for determining the size of available, renewable and non-renewable resources within the given catchment area. Currently, according to applicable legal norms in Poland, there is no reference method to determine its size (Wałęga et al., 2015). The Water Law Act of 20 July 2017 states that for individual water-legal permits, Q_n flows constitute a defined part of mean low flows (*MLF*), depending on the type of activity covered by the water-legal permit (Dz. U. 2017 item 1566).

In the case of controlled catchments, *MLF* flows are determined using the direct method, based on observational series of daily low flows. In the uncontrolled catchments, *MLF*s can be estimated based on the so-called empirical formulas, for instance, the Punzet formula, while bearing in mind certain limitations resulting from the applicability of the latter (Kokoszka, 2014). Empirical formulas constitute a generalization of information on flows collected for a larger number of water gauge profiles, by linking flow values with physiographic and meteorological factors influencing the outflow from the catchment (Wałęga and Młyński, 2015; Młyński et al., 2018).

The empirical formulas currently used in Poland for estimating *LF* and *MLF* flows have been developed mainly on the basis of hydrometric material from 1951–1980. Currently, they require verification or updating, which is directly related to the availability of more up-to-date as well as longer observational series of characteristic flows. Moreover, in the light of climatic changes as well as changes in land use within the catchment, the use of empirical formulas developed in the last century may raise justified doubts (Wałęga et al., 2014). Bearing in mind that *MLF* flows constitute the basis for determining the volume of Q_n flows used to estimate the reserve of water resources in a given region. The objective of this work was to verify the empirical formulas for estimating *MLF* flows in the aspect of estimating Q_n flows in selected mountain catchments of the Upper Vistula water region.

DESCRIPTION OF THE STUDIED AREA

The research was carried out for 10 mountain catchments located in southern Poland. The location of the studied catchments is shown in Figure 1. Table 1 shows the values of selected physiographic and meteorological characteristics of the catchment: *A* – catchment area (km^2), *I* – incline of the main watercourse (-), H – medium height of the catchment (m), *N* – soil non-permeability index (%), *P* – average annual atmospheric precipitation (mm).

Table 1. Values of the investigated physiographic parameters for analysed catchments

River	*A*, km^2	*I*, -	*H*, m	*N*, %	*P*, mm
Woda Ujsolska	106.6	0.049	319.0	72	1005
Żabniczanka	23.4	0.182	859.5	72	1094
Skawa	123.7	0.015	564.5	77	840
Krzczonówka	92.9	0.028	494.0	75	886
Potok Kościelski	36.4	0.103	1210.0	75	1527
Lubieńka	48.1	0.108	505.0	80	902
Mszanka	174.0	0.030	553.0	81	944
Kamienica Nawojowska	237.7	0.016	540.5	82	901
Sękówka	122.7	0.023	547.0	84	791
Biała	212.2	0.018	566.5	85	890

MATERIAL AND METHODS

Data for the analysis, in the form of the observational series of daily flows (Q_d) in the years 1985–2014, were obtained from the Institute of Meteorology and Water Management, of the National Research Institute in Warsaw. Subsequently, the studies were carried out according to the following stages: statistical verification of the significance of the *LF* flow trend, determining the value of *MLF* flows, determining the value of water reserves with a specific level of certainty.

Fig 1. Location of investigated catchments in upper Vistula basin

STATISTICAL VERIFICATION OF DATA

Statistical verification of the data was performed with respect to *LF* flows using the Mann-Kendall (MK) test. The zero hypothesis H_0 of the test assumes no monotonic trend of the data, whereas the alternative hypothesis H_1 states that such trend does exist. The calculations were carried out for the significance level of α = 0.05. Mann-Kendall's *S* statistic was determined based on the following equation (Banasik and Hejduk, 2012; Rutkowska and Ptak, 2012):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}\left(x_j - x_k\right) \tag{1}$$

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} 1 \text{ for} \left(x_j - x_k\right) > 0 \\ 0 \text{ for} \left(x_j - x_k\right) = 0 \\ -1 \text{ for} \left(x_j - x_k\right) < 0 \end{cases} \tag{2}$$

where:

n – number of elements in the time series.

Normalised *Z* statistic was calculated from the following equation:

$$Z = \frac{S - \operatorname{sgn}(S)}{Var(S)^{1/2}} \tag{3}$$

where:

Var(*S*) – variance *S*, determined from the equation:

$$Var(S) \frac{1}{18} \cdot \left(n \cdot (n-1) \cdot (2 \cdot n + 5)\right) \tag{4}$$

The main assumption of the *MK* test applied here is the lack of autocorrelation in a series of data. In the case of the analysis of *LF* flows, such correlations may occur, which in turn leads to an underestimation of the variance *Var*(S). Therefore, an adjustment for variance correction is included, calculated only for data with significant partial autocorrelation (Baran-Gurgul and Raczyński, 2017; Młyński et al., 2018):

$$Var^*(S) = Var(S) \cdot \frac{n}{n_s^*} \quad (5)$$

where:
$\frac{n}{n_s^*}$ – effective number of observations, calculated as:

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \cdot \sum_{k=1}^{n-1}(n-k)(n-k-1)(n-k-2)\rho_k \quad (6)$$

where:
k – adjustment;
ρ_k – value of the next significant autocorrelation coefficient.

DETERMINING THE VALUE OF MEAN LOW FLOWS

The average *MLF* flows were determined based on the observational series of Q_d flows for the investigated catchments in the years 1985-2014 (direct method) and using empirical formulas: Punzet's and Stachý's. The Punzet formula for estimating *MLF* flows in mountainous catchments is as follows (Punzet, 1981):

$$MLF = 10^{-3} \cdot MLF \cdot A,\ m^3 \cdot s^{-1} \quad (7)$$

where:
MLF – unit mean low flow [dm³ · s⁻¹ · km⁻²];
A – catchment area [km²].

The unit mean low flow is estimated as follows:

$$MLF = 0.00807 \cdot H^{1.21815} \cdot P^{0.1722} \cdot I^{0.3273} \cdot N^{-1.0504} \quad (8)$$

where:
H – mean height of the catchment [m.a.s.l.];
P – mean annual precipitation in the catchment [mm];
I – longitudinal incline of the watercourse [m · km⁻¹];
N – Boldakov's soil non-permeability index [%].

Stachý's formula for calculating *MLF* flows in Carpathian catchments is described by the following correlation (Stachý, 1990):

$$MLF = 2.613 \cdot 10^{-4} \cdot A^{1.07} \cdot SSq_p^{0.55} \cdot i_r^{0.35},\ \mathrm{m^3 \cdot s^{-1}} \quad (9)$$

where:
A – catchment area [km²];
SSq_p – unit mean flow from the multiyear period from groundwater flow [dm³ · s⁻¹ · km⁻²];
i_r – incline of the watercourse [m · km⁻¹].

In order to determine individual physiographic characteristics of the catchment, the QGIS 2.18 software was used. The areas of the investigated catchment (*A*) have been determined on the basis of the Map of the Hydrographic Division of Poland (MPHP 2010). Mean catchment height (*H*) and inclines of the watercourse (*I*), (i_r) were determined based on the Map of Hydrographic Division of Poland and on the Digital Terrain Model (NMT), obtained from the United States Geological Survey, with a grid resolution of about 30 m. Mean annual precipitation in the catchment (*P*) was determined using the reverse distance method based on meteorological data, in the form of observation series of daily precipitation, in the years 1985–2014, obtained from the Institute of Meteorology and Water Management of the National Research Institute in Warsaw. The mean unit flow from underground water supply SSq_p was determined based on the Hydrological Atlas of Poland (Stachý, 1987).

In order to verify the analysed empirical formulas, the values of the relative error of estimation σ of *MLF* flows were determined using the Punzet and Stachý formula:

$$\sigma = \frac{MLF_e - MLF}{MLF} \cdot 100,\ \% \quad (10)$$

where:
MLF_e – mean low flow calculated from empirical formulas [m³ · s⁻¹];
MLF – mean low flow calculated on the basis of hydrometric observations [m³ · s⁻¹].

Above-zero values of relative errors indicate the overestimation of *MLF* flows determined using the formulas analysed herein, as compared to hydrometric observations. Below-zero σ error values indicate underestimation of *MLF* flows calculated with empirical formulas, in comparison to hydrometric observations.

DETERMINING WATER RESERVE WITH A SPECIFIED LEVEL OF CERTAINTY

Available water resources (water reserve) were determined as the difference between the characteristic flow and the baseflow (Ciepielowski, 1999). Because water reserve with a given level of certainty were analysed, their value in the studied catchments was calculated as:

$$ZD = Q_{gw-95\%} - Q_{nh},\ \ \mathrm{m^3 \cdot s^{-1}} \tag{11}$$

where:

$Q_{gw=95\%}$ – flows with the probability of 95% [$\mathrm{m^3 \cdot s^{-1}}$];

Q_{nh} – baseflow [$\mathrm{m^3 \cdot s^{-1}}$].

In this work, the amount of water reserves for municipal supply purposes was adopted – hence a 95% certainty level was assumed (Szpindor, 1974). $Q_{gw=95\%}$ flows were determined based on the course of multi-year flow guarantee curves, designated for the studied catchments. The baseflow was calculated using the following formula (Kostrzewa, 1977):

$$Q_{nh} = k \cdot MLF,\ \ \mathrm{m^3 \cdot s^{-1}} \tag{12}$$

where:

k – parameter depending on the hydrological type of the river, and the surface area of the catchment [–];

MLF – mean low flows determined based on the hydrometric material and verified empirical formulas [$\mathrm{m^3 \cdot s^{-1}}$].

RESEARCH RESULTS AND THEIR ANALYSIS

In the first stage of the study, an analysis of the statistical significance of the *LF* flow trend was conducted, using the Mann-Kendall test for the studied catchments in the multi-year period 1985–2014. The results of the analysis are summarized in Table 2.

Based on the results summarized in Table 2, it was found that for the analysed multi-year period there has been no significant statistical trend of *LF* flows in the studied catchments. This is confirmed by the p_c value of the Mann-Kendall test, in each case at a level above 5%. Lack of statistically significant trends means that

Table 2. Results of the statistical analysis conducted by applying MK test to the investigated catchments

River	Z_c	p_c	$Var(S)_c$	n/n^*	Z	p	$Var(S)$
Woda Ujsolska	1.039	0.299	2700.458	0.863	0.965	0.334	3128.333
Żabniczanka	0.542	0.588	1363.483	0.441	0.360	0.719	3089.667
Skawa	–0.564	0.573	1258.857	0.404	0.358	0.720	3119.000
Krzczonówka	0.599	0.549	1885.149	0.602	0.465	0.642	3131.000
Kirowa Woda	2.938	0.003	704.755	0.225	1.394	0.163	3133.000
Lubieńka	–0.493	0.622	1487.829	0.477	–0.340	0.734	3116.000
Mszanka	–1.821	0.069	2027.701	0.647	–1.465	0.143	3133.000
Kamienica Nawojowska	–0.257	0.797	739.622	0.236	–0.125	0.901	3134.667
Sękówka	1.313	0.189	794.242	0.254	0.662	0.508	3124.667
Biała	–1.407	0.159	1163.542	0.375	–0.862	0.389	3099.667

Z_c – modified value of the normalised MK statistic; p_c – modified value of the test probability, $Var(S)_c$ – modified value of the variance, n/n^* – effective number of observations, Z – the value of the normalised MK statistic, p – test probability, $Var(S)$ – variance the investigated random variables derive from the same general population. Thus, in the analysed multi-year period, no factor appeared to be significantly affecting the processes that shape low flows. The results obtained from the research can be linked to the results concerning the trend analysis of the factors significantly affecting the flow of waters in the catchments of the Upper Vistula water region. Research carried out by Pińskwar (2010) and Niedźwiedź et al. (2014) showed no significant trends regarding the indicators describing daily precipitation. Analyses carried out by Falarz (2002) confirmed the lack of significant trends for the duration of snow cover remaining in mountainous catchments. The supply of rivers in the Upper Vistula water region comes mainly from snowmelt runoff and from precipitation – hence it is assumed that the rhythm of effluents is repeated by the low flows.

To estimate the value of *MLF* flows, hydrometric material and empirical formulas of Punzet and Stachý were used. The results of the calculations and of the empirical formulas verification are summarized in Table 3 and Figure 2.

Based on the value of *MLF* flows compiled in Table 3 and Figure 2, significant differences were found between the analysed characteristics. In the case of *MLF* flows calculated using the Punzet formulas, most of them are higher than the *MLF* determined using the direct method. Values of relative errors in estimating the *MLF* flow with the Punzet formula ranged between 5.6% (for Lubieńka) and –73.9% (for the Biała river). The average relative error amounted to 43.4%. The *MLF* flows calculated using the Stachý formula were in most cases lower than the actual values. The relative errors in determining the *MLF* flow with the Stachý formula ranged from 3.8% (for Woda Ujsolska) to –205.4% (for Skawa), with the mean value of 54.9%.

Table 3. Values of mean low flows calculated by direct method and by empirical formulas

River-cross-section	*MLF*, $m^3 \cdot s^{-1}$	*Calculated MLF*, $m^3 \cdot s^{-1}$	
		Punzet	Stachý
Woda Ujsolska	0.300	0.123	0.288
Żabniczanka	0.093	0.141	0.132
Skawa	0.108	0.177	0.330
Krzczonówka	0.240	0.142	0.299
Potok Kościelski	0.415	0.279	0.270
Lubieńka	0.117	0.111	0.238
Mszanka	0.467	0.291	0.597
Kamienica Nawojowska	0.478	0.307	0.456
Sękówka	0.241	0.173	0.171
Biała	0.163	0.292	0.283

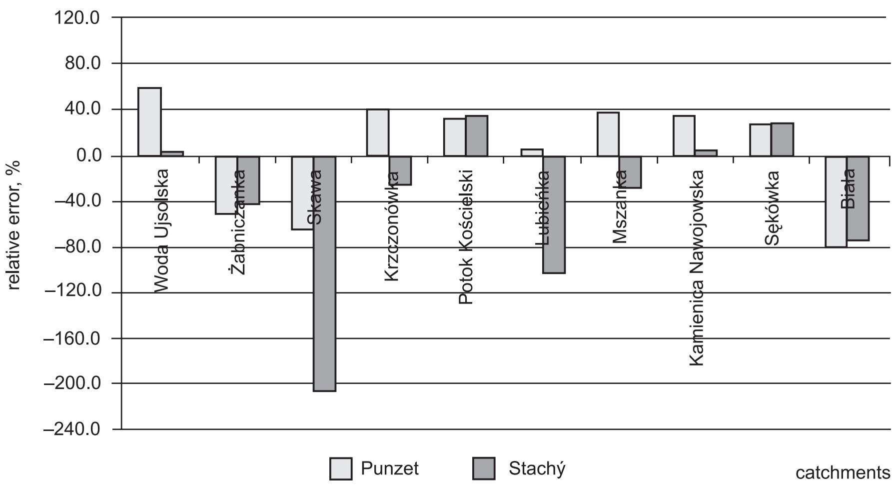

Fig. 2. Mean relative errors in mean low flows derived by empirical formulas

The obtained results of the verification of empirical formulas for calculating *MLF* flows may be due to the fact that these formulas are dedicated mainly to natural catchments, i.e. those in which the outflow is not disturbed by anthropogenic pressure. The catchments under investigation are located in southern Poland – that is within an area where the impact of human activity on the river regime in recent decades was particularly significant. This applies mainly to mountainous basins, which very often are characterized by a significant concentration of human pressure, such as surface water intakes, water discharges, or the introduction of hydro-technical structures (RZGW, 2012). When analysing the obtained results, it should also be emphasized that due to the on-going meteorological changes and changes to the land use within the catchment, as well as the availability of longer and more current series of characteristic flows, empirical formulas should be systematically verified and updated. It also needs to be stressed that the number of independent variables in the model should be optimal. In addition to carrying the information about the value of the dependent variable, each independent variable is also burdened with uncertainty resulting from the observation series of such a characteristic. Furthermore, let us point out that empirical formulas should be constructed in the possible way from a methodological point of view. This statement refers to the fact that the currently used formulas were developed in times of limited access to digital computing techniques. This meant limiting the possibilities of their analysis in terms of the quality of the obtained results. Moreover, we should take into account the development of measurement technologies used to acquire land data as well as of spatial information systems that allow for the automatic calculation of the physiographic parameters of the catchment, which then form the basis for the development and use of empirical models for calculating characteristic flows. In addition, attention should be paid to the fact concerning the increasing possibility of obtaining current hydro-meteorological data. The application of spatial information systems, together with the use of current hydro-meteorological data, allows for a more accurate estimation of characteristic flows than in had been the case with traditional materials (topographic maps, hydrological and meteorological atlases) used in previous years, when estimating flows using empirical formulas (Węglarczyk, 2015).

A complement to the conducted research was the analysis of available resources with a 95% certainty ($ZD_{gw = 95\%}$), where baseflows were estimated on the basis of *MLF* calculated using the direct method as well as the Punzet and Stachý models. The results obtained from the analysis are summarized in Table 4. Figure 3 shows the number of inhabitants that it is possible to supply with water, with the available resources calculated by the analysed methods.

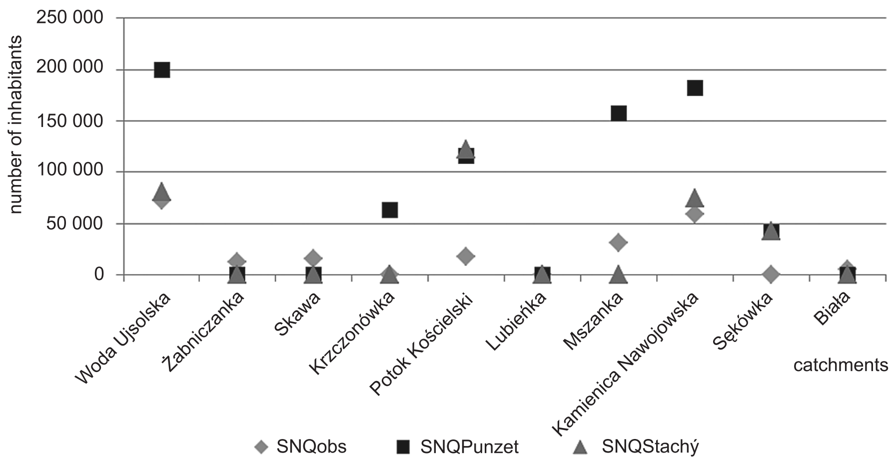

Fig. 3. Number of inhabitants that it is possible to supply with water from available water resources derived regarding to mean low flow obtained from analysed methods

Table 4. Available water resources derived based ion mean low flows obtained from the analysed methods

River	ZD [m³ · s⁻¹]	ZD_{Punzet} [m³ · s⁻¹]	$ZD_{Stachý}$ [m³ · s⁻¹]
Woda Ujsolska	0.100	0.277	0.112
Żabniczanka	0.017	–0.031	–0.022
Skawa	0.022	–0.047	–0.200
Krzczonówka	–0.010	0.088	–0.069
Potok Kościelski	0.025	0.161	0.170
Lubieńka	–0.007	–0.001	–0.128
Mszanka	0.043	0.219	–0.087
Kamienica Nawojowska	0.082	0.253	0.104
Sękówka	–0.011	0.057	0.059
Biała	0.007	–0.122	–0.113

ZD – available resources determined based on the *MLF*, using statistical method; ZD_{Punzet} – available resources determined based on the *MLF*, calculated using the Punzet's formula; $ZD_{Stachý}$ – available resources determined based on the *MLF*, calculated using the Stachý's formula

Based on the values in Table 4, it was found that $ZD_{gw=95\%}$ determined on the basis of *MLF* flows, estimated with the Punzet formula, in 6 studied catchments are higher than the $ZD_{gw=95\%}$ determined on the basis of hydrometric observations. On the other hand, the negative values of these resources were recorded for the 4 catchments, where only for Lubieńka in Lubień section is the result supported by hydrometric observations. In the case of $ZD_{gw=95\%}$ determined on the basis of *MLF* flows, calculated using the Stachý formula, higher values of these resources were found in 4 studied catchments, as compared to resources determined on the basis of hydrometric material. In contrast, in 6 analysed catchments, negative values of these resources were found, where only for the 2 basins is this is convergent with the values obtained on the basis of hydrometric material. It should be emphasized that the variable size of available resources, determined on the basis of the analysed methods, affects a significant diversification of the potential number of inhabitants that it is possible to supply with water from surface water sources (see: Fig. 3). This underscores the problem of estimating baseflows in relation to the *MLF* in uncontrolled catchments. It should be noted that obtaining higher values of *MLF* flows using empirical formulas would lead to the determination of Q_{nh} flows at too high a level. This is beneficial in terms of environmental considerations – however, it may cause a barrier to socio-economic development within the given catchment (Operacz et al., 2018). In addition to the significant impact on the quantitative status of the catchment's water resources, the *MLF* is assumed to be the measure for assessing the possibility of introducing a specific amount of sewage into the receiving body of water, which is a measurable aspect in the quality assessment of such a facility (Kurek et al., 2018). Therefore, it would be justified to conduct analyses related to establishing and verifying current methods for calculating *MLF* flows in uncontrolled catchments.

CONCLUSIONS

Based on the conducted analyses, it was found that in the examined multi-year period there were no factors significantly affecting the formation of low flows, in the investigated catchments of the upper Vistula water region. This is evidenced by the lack of statistically significant trends for *LF* flows in the analysed catchments. The obtained results also indicated that there is a need to update empirical formulas for calculating *MLF* flows in mountainous catchments. In conducting such research, anthropogenic pressure for the analysed areas should be taken into account. This is confirmed by the value of relative errors in the estimation of *MLF* flows in relation to flows calculated using the direct method. In addition, it was found that after considering the baseflow, which takes into account *MLF* calculated by the analysed methods, the available resources for the same catchments were different for different computation methods. This contributes to the problems associated with the determination of resources for ungauged catchments, where they can be set at a too high or too low a level in relation to the actual flow conditions. Therefore, it is necessary to conduct further analyses regarding obtaining reliable values of *MLF* flows in ungauged catchments.

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WERYFIKACJA WZORÓW EMPIRYCZNYCH DO WYZNACZANIA PRZEPŁYWÓW ŚREDNICH NISKICH W ASPEKCIE SZACOWANIA ZASOBÓW DYSPOZYCYJNYCH

ABSTRAKT

Cel pracy

Celem pracy była weryfikacja wzorów empirycznych do wyznaczania przepływów średnich niskich (SNQ) w aspekcie szacowania zasobów dyspozycyjnych, dla wybranych zlewni górskich Polski południowej. Analizie poddano wzory empiryczne Punzeta i Stachý.

Materiał i metody

Badania wykonano wg następujących etapów: analiza istotności trendu przepływów niskich (*NQ*), określenie wartości przepływów *SNQ* metodą bezpośrednią oraz wzorami Punzeta i Stachý, wyznaczenie zmienności zasobów dyspozycyjnych w odniesieniu do przepływu *SNQ* wyznaczonego różnymi metodami.

Wyniki i wnioski

Na podstawie przeprowadzonych badań stwierdzono brak statystycznie istotnych trendów przepływów *NQ* w zlewniach badawczych. Wskazano na znaczne różnice pomiędzy wartościami przepływów, określonymi za pomocą wzoru Punzeta i Stachý, w odniesieniu do przepływu *SNQ* wyznaczonego na bazie materiału hydrometrycznego,

Słowa kluczowe: wzory empiryczne, przepływ średni niski, zasoby dyspozycyjne