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REGIONAL CONDITIONS FOR MAXIMUM PROBABLE DISCHARGE IN POLAND'S RIVERS

Abstract: The purpose of this study was to obtain and verify the methods of catchment regionalization for annual maximum discharge. An identification of Polish rivers was performed based on regional frequency analyses including recognition of regions homogeneous with respect to their physical properties and river flow parameters. The results suggest a division into two regional groups: mountain and lowland catchments. Statistical tests verify the regionalization obtained and allow to calculate regional probability curves for these two catchment groups. The results obtained may be helpful in the analysis of floods in ungauged catchments and in those where hydrological observations were performed during a short period, especially when the dependence of the maximum probable flows on their physico-geographical features in catchments under analysis has been proved.

Key words: annual probable maximum flow, regional frequency analysis, flood, recurrence period, catchment typology.

INTRODUCTION

The method of regional flood frequency analysis can be applied when hydrological data necessary for the estimation of peak flow parameters are lacking or when the available information is insufficient for this purpose. Usually, research is performed in two stages. First, homogeneous catchments are identified and joined into homogeneous hydrological regions. Next, the probability of the occurrence of a flood event in a catchment from a given region is calculated, using selected methods of regional analysis. In this method, the recurrence interval of an extreme flow is taken as being the reciprocal of the probability of its occurrence: $T = 1/p$. The homogeneity of regions is usually defined by means of statistical methods as the closest neighbourhood in geographical space (the similarity of the catchments form-ing the given region), or else as the occurrence of significant differences from the remaining regions in geographical space. The identification of homogeneous hydrological regions is usually done by grouping catchments based on their physicogeographical similarity (Acreman, Sinclair, 1986; McKerchar and Pearson, 1990; Bayliss, Reed, 2001; Ouarda et al., 2001; Chokmani, Ouarda, 2004; Zhang Jingyi, Hall, 2004; Merz, Blöschl, 2005; Cunderlik, Burn, 2006; Ouarda et al., 2006; Shu, Ouarda, 2007).

Another approach to regionalization, recently more popular among hydrologists, is based on the similarity of peak flow seasonality. In models of this type the selection of homogeneous regions is based on the study of peak flow seasonality in various measurement stations and on determination of the genetic type of peak flows. The determination of seasons in each station (the number of the main seasons, the beginning and end dates of each season) is used to identify types of catchments with similar seasonal peak flow behaviour. The main advantage of this approach is the use of actual data for the description of peak flow seasonality, thanks to which the results of the grouping are more reliable. The information on the time of peak flow occurrence, taken into account when delimiting hydrologically homogeneous regions, allows also to distinguish overlapping episodes with various genesis, such as spring snow melt (in northern latitudes) or heavy rainfall in the summer half-year (Cunderlik, Burn, 2002; Ouarda et al., 2006).

The first step in regional analysis is the selection of similar catchments (catchment groups). Various approaches have been applied for searching for similarity of catchments and grouping them in regions. Both peak flow parameters and physical characteristics of catchments have been taken into account. Forty catchments have been analysed, for which data on highest flows in 1975-2006 were available (Table 1).

To find a measure of physicogeographical similarity of catchments, ten parameters (characteristics) have been taken into account: topographical area [km^2], length of river network [km], density of river network [km/km^{-2}], length of the main stream [m], mean main stream slope [%], catchment perimeter [km], catchment length [km], share of forests in the total area [%], and the geographical coordinates of the geometrical centre of the catchment [m] (Table 2).

Catchment parameters have been identified from the following digital maps: *Maps of Hydrographic Division/Partition of Poland* (MPHP – base scale 1:50 000), *Corine Land Cover* (degree of detail corresponding to a map in the scale 1:100 000) and *Numerical Terrain Model DTED Level 2* (degree of detail corresponding to a map in the scale 1:50 000). Hydrological data have been taken from the *Hydrological Yearbooks of Surface Waters* (up to 1982) and from the IMGW data base compiled specifically for the purpose of the project (data for the years 1984-2006).

Table 1. Analysed river basins

Lp.	River – profile	A [km^2]	WWQ [m^{3}s^{-1}]	Flood origin
1	Biała Tarnowska – Grybów	207	180.0	rainfall
2	Biała Lądecka – Lądek Zdrój	163	270.0	rainfall
3	Cicha Woda – Zakopane	58,4	69.2	rainfall
4	Czarna Hańcza – Czerwony Folwark	488	11.6	snow melt
5	Drawa – Drawsko Pomorskie	592	18.2	snow melt
6	Ełk – Ełk	829	38.0	snow melt
7	Gwda – Ptusza	2042	37.2	snow melt
8	Hoczewka – Hoczew	169	129.0	rainfall
9	Ina – Goleniów	2138	86.4	snow melt
10	Jasiołka – Zboiska	264	159	rainfall
11	Kamienica – Nowy Sącz	237	188.0	rainfall
12	Kocierzanka – Łękawica	36,5	30.4	rainfall
13	Krutynia – Ukta	653	11.1	snow melt
14	Liwiec – Łochów	2471	276.0	snow melt
15	Łubinka – Nowy Sącz	66,6	110.0	rainfall
16	Łyna – Smolajny	2302	50.6	snow melt
17	Nurzec – Boćki	535	67.8	snow melt
18	Omulew – Krukowo	1209	31.6	snow melt
19	Orzyc – Krasnosielc	1326	107.0	snow melt
20	Osława – Szczawne	300	229	rainfall
21	Płonia – Żelewo	1026	20.1	rainfall
22	Potok Kościeliski – Kościelisko-Kiry	34,7	35.0	rainfall
23	Rega – Łobez	616	25.1	snow melt
24	Rega – Trzebiatów	2644	87.0	snow melt
25	Rospuda – Raczki	300	25.7	snow melt
26	San – Dwernik	418	243.0	rainfall
27	Sękówka – Gorlice	122	450.0	rainfall
28	Skawa – Jordanów	96,8	98.0	rainfall
29	Skora – Chojnów	266	180.0	rainfall
30	Skora – Zagrodno	166	138.0	rainfall
31	Skrwa – Parzeń	1490	132.0	snow melt
32	Solinka – Terka	309	254.0	rainfall
33	Soła – Rajcza	254	373.0	rainfall
34	Soła – Żywiec	783	688.0	rainfall
35	Stryszawka – Sucha	140	97.7	rainfall
36	Świder – Wólka Mlądzka	860	115.0	snow melt
37	Wda – Czarna Woda	728	14.9	snow melt
38	Wda – Wawrzynowo	422	7.1	snow melt
39	Wierzyca – Bożepole Szlach.	406	11.1	rainfall
40	Wisła – Wisła	54.6	48.7	rainfall

FLOOD PARAMETERS AS A FUNCTION OF THE CATCHMENTS PHYSIOGEOGRAPHICAL FEATURES

First, the relationship between the physicogeographical parameters of a catchment and the highest annual flow in 1974-2006 has been sought. The distribution of the highest annual flows (*WWQ*) as a function of the catchment surface area (*A*) allowed to distinguish three catchment groups. The relationships *WWQ = f(A)* in the groups singled out have been described by exponential equations (Fig. 1).

The first group consisted of 15 mountain catchments (of the Biała, Biała Lądecka, Cicha Woda, Jasiołka, Kamienica, Kocierzanka, Łubinka, Osława, Potok Kościeliski, San, Sękówka, Skawa, Solinka, Soła, Stryszawka rivers and the source catchment of the Vistula river), in which the highest flows are formed by torrential precipitation (Fig. 1). This relationship is described by the empirical equation (1) derived as:

$$WWQ_1 = 2.1052A^{0,846} \tag{1}$$

where: *WWQ* – the highest flow of the river in 1975-2006 [m^3/s], *A* – surface area of the topographical catchment [km^2].

The coefficient of determination R^2 of the variables analysed, indicating the strength of correlation, is 0.74.

The second group consists of six lowland catchments: the Liwiec, Nurzec, Orzyc, Świder, Skrwa and Rospuda rivers. The highest flow as a function of surface area of this catchment type is also expressed by the empirical equation

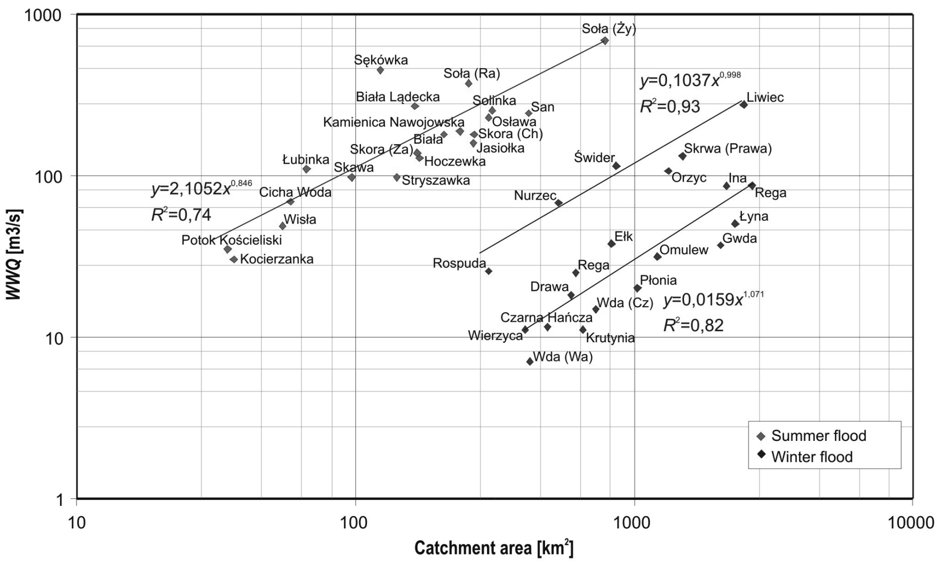

Fig. 1. Maximum flow *WWQ* [m^{3}s^{-1}] in relation to the area of topographical catchment *A* [km^2]; R^2 – coefficient of determination

(2). The determination coefficient confirms a strong correlation (R^2 = 0.93):

$$WWQ_2=0.1037A^{0.998} \tag{2}$$

The remaining group, consisting of 12 lakeland catchments, is described by the relationship (3) with a somewhat weaker strength of correlation (R^2 = 0.82):

$$WWQ_3=0.0159A^{1.071} \tag{3}$$

Another approach to catchment analysis uses the coefficient of the highest flow (k) per unit area of the topographical catchment:

$$k=WWQ/A^{0.5} \tag{4}$$

The coefficient k allowed to order the catchments in a different way (Fig. 2). In lowland catchments its value does not exceed 5.6 m^{3}s^{-1}km^{-2}, while in lakeland catchments, $k \le 2$ m^{3}s^{-1}km^{-2} . The most distinct are all the mountain catchments, for which $k \ge 6$ m^{3}s^{-1}km^{-2}. In this group, the catchments of the Biała Lądecka, Soła and Sękówka rivers are characterised by the coefficient $k > 20$ m^{3}s^{-1}km^{-2}.

A good characteristics for comparison studies in inland water hydrology is – next to the water level and the intensity of the maximum flow – the amount of water flowing off a catchment area unit during the peak flow, i.e., the so-called specific discharge, according to the equation (5):

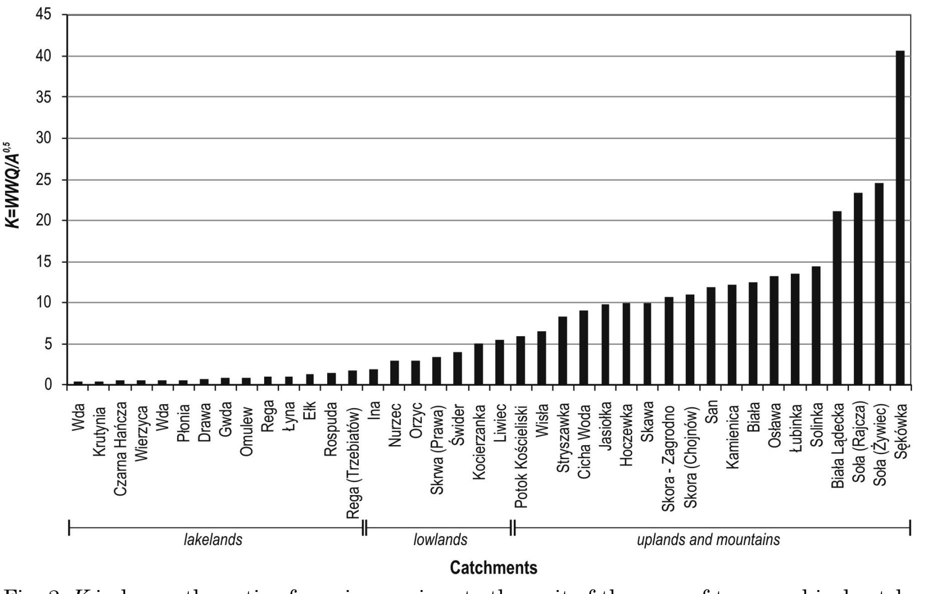

Fig. 2. K index as the ratio of maximum river to the unit of the area of topographical catchment A

$$q = \frac{1000 \cdot Q_{max}}{A} \tag{5}$$

where q – specific discharge of the flow [dm^3/s km^2 or m^3/s km^2], Q_{max} – the highest streamflow intensity measured or estimated [m^3/s], A – surface area of topographical catchment [km^2].

We can therefore calculate the maximum discharge from a unit area of the catchment. Research on this issue results from the needs of flood protection and the exact knowledge of the parameters of flood waves, as well as the conditions of flood formation in catchments of various climatic and physicogeographical features. Here the principles of classification based on regional parameters are necessary, which facilitate the comparison of various areas and the selection of analogous hydrological catchments (*World Catalogue,* 2003).

An interesting material for comparison is contained in the coefficient of the amount of maximum discharge per unit area of the catchment. The most often used coefficient k (calculated from the equation 4) has – according to the *World catalogue of maximum observed floods* (2003) – a limited application and should be taken into account in the case of catchments with surface area smaller than 500 km^2, which excluded from the analysis the catchments of the Soła, Wda, Świder and Omulew rivers. Instead, the authors of the *World catalogue of maximum observed floods* (2003) suggest the Francon coefficient (K), of the form (6):

$$K = 10\ [(1 - \log Q_{max} - 6)/(\log A - 8)] \tag{6}$$

The analysis of the variability of the coefficient K, performed by the authors in many selected catchments, indicates a clear connection between the peak flow and the surface area of the catchment. The coefficient K oscillates around the value 6. In extreme cases of the dependence on the catchment size and physicogeographical features it varies in various areas between 5.1 and 6.7.

An attempt to calculate this coefficient for certain rivers in Poland shows that K has values between 2.0 and 4.0, thus it is smaller and more variable. The authors warn, however, of its application and prefer the relationship (5) in the case of smaller catchments where local factors have greater effect. J. Rodier and M. Roche (1984) presented an approximate relationship between the variables mentioned, of the form (7):

$$WWQ \approx 500 \cdot A^{0.43} \tag{7}$$

Recently, A. Bartnik and P. Jokiel (2007, 2008), on the basis of hydrological data for Europe's rivers derived an equation showing the relationship between WWQ from several years and the surface area A, which can be written in the form (8):

$$\frac{1}{\log(WWQ)} = 0.248 + 0.483 \exp[-\log(A)] \tag{8}$$

On the other hand, J.M.O. O'Connor and J.E. Costa (2004) analysed maximum flows of America's rivers as functions of surface area and obtained a linear relationship between the probable flow *WWQ* $p = 99\%$ and $p = 90\%$ expressed by the equations (9, 10):

$$WWQ_{p99\%} = 74.0\ A^{0,53} \tag{9}$$
$$WWQ_{p90\%} = 24.3\ A^{0,52} \tag{10}$$

Numerical values obtained from the empirical relationship above were exhaustively discussed by Bartnik and Jokiel (2008).

The relative measures presented here are related to the highest peak flow of rivers as functions of the surface area of a catchment. Although the first edition of the *Catalogue* was published 25 years ago, the relationships derived and the methodology accepted later have not been fully used in Polish hydrology so far. Therefore, research has been undertaken on the relationships presented on the regional scale of Poland's rivers.

PHYSICOGEOGRAPHICAL SIMILARITY OF CATCHMENTS

Studies on regional justification of the causes of the maximum river flow formation require that a methodology be used related to the search for the similarity of physicogeographical features of catchments. The classification procedure has been performed by hierarchical grouping. This method allows to order the catchments into relatively homogeneous classes by detecting specific clusters of objects (catchments) in a topological space, based on relative distances and without taking into account spatial continuity (*cluster analysis*). The basic criterion of catchment similarity is the taxonomic distance (Gutry-Korycka, 1986; Suchożebrski, 2002; Młodak, 2006; Kot et al., 2007).

Constants in a topological space expressed by means of 10 physicogeographical parameters and identified in the catchments have been ordered to form a matrix of spatial information M_1 of dimensions ($n \times m$), where $n = 40$ is the number of catchments, $m = 9$ is the number of their parameters (Table 2). This matrix was then analysed numerically by means of the *Statistica version 8* software package.

The spatial variables introduced have been standardised so as to satisfy the conditions of comparability, summability, and normalisation, consisting in replacing the original values (parameters) with measures which follow from the relationships between the mean and the standard deviation, as in the following expression (11):

$$x'_{ij} = \frac{x_{ij} - \bar{x}_j}{\sigma_j} \tag{11}$$

where: x_{ij} – value of the jth feature of the ith catchment, $\bar{x}_j$ – average value of the jth feature, σ_j – standard deviation of the jth feature.

The mean value of a standardised variable is 0, and their variance and standard deviations are equal to 1. As a result, the matrix Z of standardised variables of dimensions ($n \times m$) has been obtained.

As we have mentioned, the classification procedure has been performed by means of hierarchical grouping. As the measure of distance between the objects i and k the Euclidean distance (d_{ik}) has been taken, calculated from the equation (12):

$$d_{ik} = \sqrt{\sum_{j=1}^{p} \left(y_{ij} - y_{kj}\right)^2} \tag{12}$$

where: y_{ij} – value of the jth feature of the ith object; y_{ij} – value of the jth feature of the kth object ($i \neq k = 1, 2, ..., n$) (Cunderlik, Burn, 2006).

The matrix of standardised data (features) $Y = \{y_{ij}\}$ has been transformed into the matrix of taxonomical distances $D = \{d_{ik}\}$. Next, pairs of clusters p and q ($p < q$, $p = q = 1, 2, ..., n$) have been found, corresponding to the smallest distances between the catchments. The consecutive clusters p and q have been joined into one new cluster, and then transformed into a distance matrix according to the equation (13):

$$d_{ir}^2 = \alpha_p d_{ip}^2 + \alpha_q d_{iq}^2 + \beta d_{pq}^2 + \gamma \left| d_{ip}^2 - d_{iq}^2 \right| \tag{13}$$

where: d_{ir} – distance between clusters i and r; d_{ip} – distance between clusters i and p; d_{iq} – distance between clusters i and q; d_{pq} – distance between clusters p and q; α, β, γ – parameters of the transformations depending on the cluster analysis method applied.

This method is repeated until only one cluster is obtained. In hierarchical grouping the variable of probability threshold is used; that is, the so-called sequential criterion of element property is applied. In the first stage of the procedure one cluster is formed of the two most similar catchments; as the threshold is lowered, larger numbers of catchments form groups, until all the spatial units are joined into one class.

Out of many available methods of cluster analysis, J. H. Ward's procedure has been applied. It consists on joining such clusters in which the sum of squares of distances from the gravity centre of the new cluster is minimal (Ward, 1963). Groups created with this method are characterised by a similar number of elements and a greater compactness in space as compared with other classification methods. This method is recommended when the objects form naturally separated clusters (Zeliaś et al., 1989; Grabiński, 1992; Sobczyk, 1995; Młodak, 2006); this was assured by the digital analysis used.

The results of catchment classification as related to the search for their similarity is presented by a hierarchical dendrogram (Fig. 3). The similarity of the units comprising a given group decreases with each step of the group-

Table 2. Parameters and statistics of spatial catchment variables

Characteristics		Statistics							
		Mean	Median	Minimum	Maximum	Variation	Standard deviation	Skewness	Kurtosis
Area [km^2]		680.6	412.0	34.7	2644.3	5.2802E+05	726.6	1.502	1.289
Length of the river network [km]		352.5	290.7	32.0	981.2	7.0272E+04	265.1	0.984	0.291
Density of the river network [km/km^2]		1.6	1.8	0.4	2.3	3.9539E-01	0.6	-1.064	-0.155
Depression of the main stream [m]		445.9	462.5	212.0	672.0	2.0804E+04	144.2	-0.194	-0.813
Average slope of the main stream [%]		2.4	1.7	0.5	6.7	3.2681E+00	1.8	1.410	1.322
Length of the river basin [km]		25.4	21.8	8.6	80.7	3.4264E+02	18.5	1.834	3.706
Forestation [%]		55.0	53.3	20.1	91.1	5.7348E+02	23.9	-0.172	-1.379
Coordinates of the geometric centre [m]	X	556167.8	605738.0	230348.0	783594.0	2.9652E+10	172197.9	-0.626	-0.876
	Y	393137.2	362500.0	147840.0	707334.0	4.7929E+10	218927.9	0.191	-1.831
River basin perimeter [km]		157.4	109.3	27.8	474.2	1.3866E+04	117.8	1.046	0.283

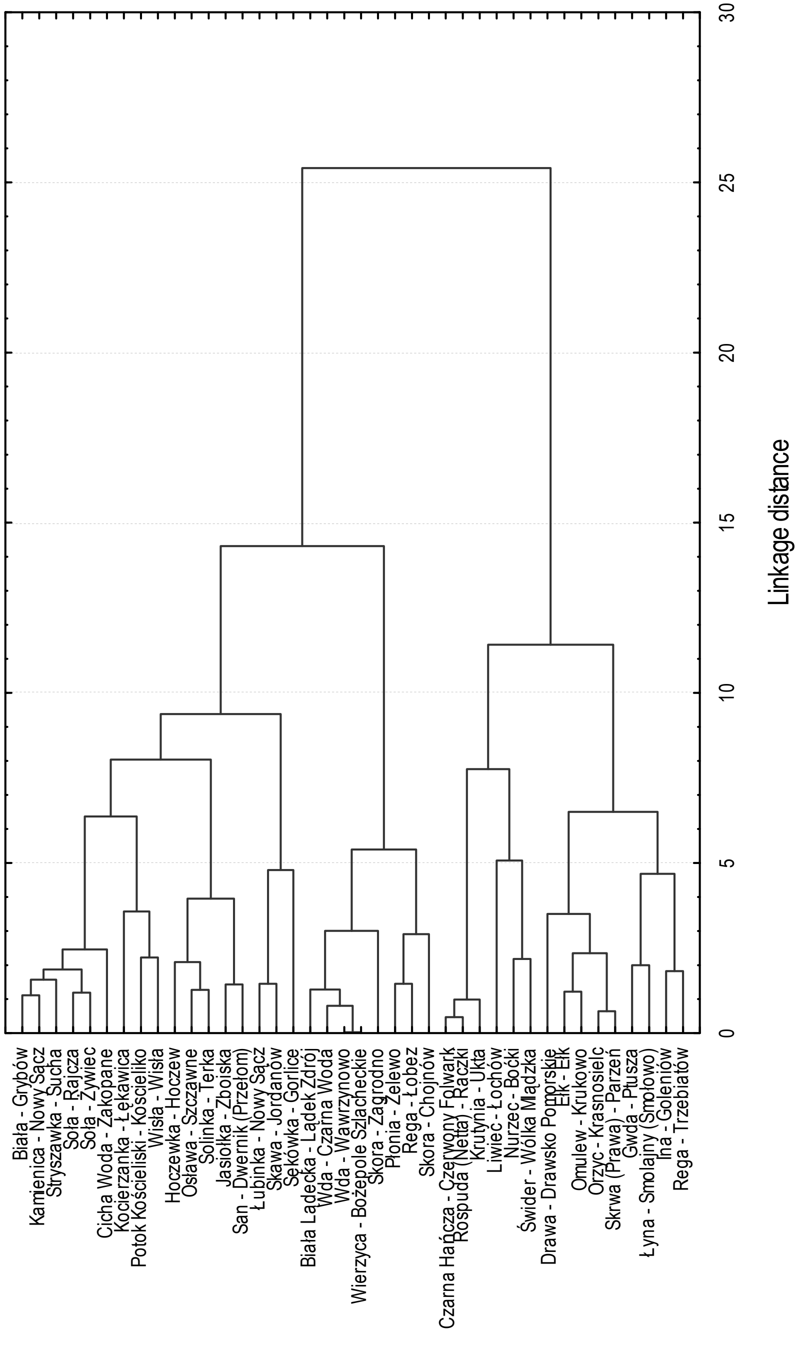

Fig. 3. Hierarchical dendrogram of catchment grouping based on Ward method

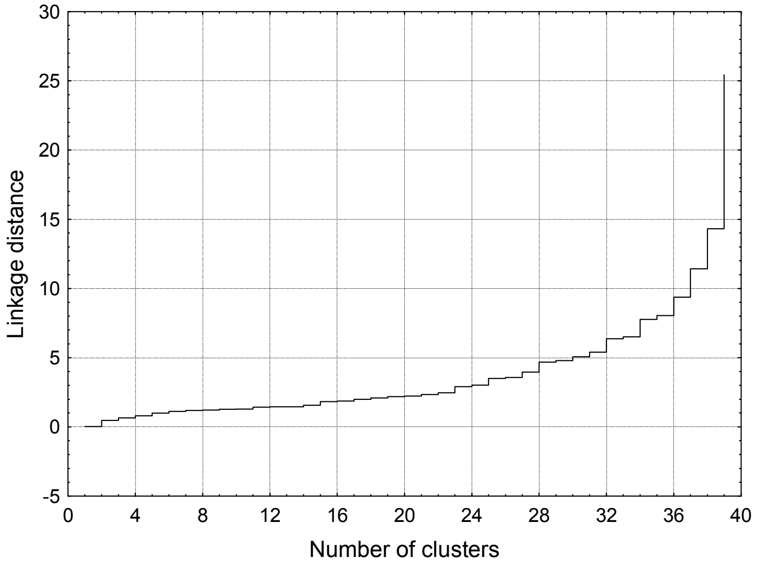

Fig. 4. Binding distances in successive steps of catchment grouping

ing process. Greater generalisation causes an increase of the distance between the elements, thus a loss in details of spatial information. The choice of the appropriate number of classes has been made by means of the analysis of the grouping process (Fig. 4). However, only objective measures of grouping quality verify the homogeneity of the elements which form clusters and test the variety of the next clusters as well as the size of groups being formed.

A simple criterion for estimation of the optimal number of classes, which uses the distance between the consecutive clusters, is calculated by means of the following expression (14):

$$q_j = \frac{d^{i}_{pq}}{d^{i-1}_{pq}} \tag{14}$$

where: d_{pq} – distance between the clusters p and q (the linkage distance), i – grouping stage (i = 2, ..., n).

As the optimal number of classes we take the number corresponding to the maximum value of the coefficient q_j (Zeliaś et al., 1989; Grabiński, 1992). According to the formula (14), the grouping should be halted at the level 37 or 38, because the distance between the consecutive clusters is then largest: it is 2.09 and 2.84, correspondingly (Table 3). Only 3 or 2 groups (types) are then obtained from among 40 catchments analysed.

Table 3. Correctness and quality indicators of catchment division into groups (explanation in the text)

Grouping level	Number of clusters	Binding distances	Distance difference	Indicators of the division quality	
				MJP 28	MJP 44
33	7	6.5027	1.26	0.17	0.27
34	6	7.7598	0.28	0.18	0.32
35	5	8.0373	1.34	0.18	0.77
36	4	9.3801	2.04	0.12	0.56
37	3	11.4169	2.89	0.10	0.22
38	2	14.3124	11.11	0.08	0.19
39	1	25.4242		0.49	0.05

There are many measures of grouping quality used for testing the correctness of the grouping results (*MJP*). In the present research, the measure *MJP 44* has been applied, expressed by the equation (15) (Zeliaś et al., 1989; Grabiński, 1992; Młodak, 2006):

$$MJP44 = \max\left[\left[\sum_{p=1}^{n_l}\left\{d\left(0_p,\bar{0}_l\right)\right\}^2\right]\Big/ n_l\right]\Big/\min\left[\min_q\left\{\left(\bar{0}_l,\bar{0}_q\right)\right\}^2\right] \tag{15}$$

where: n_l – number of objects in the l-th group; k – number of clusters; $d(\mathrm{O}_p, \bar{\mathrm{O}}_l)$ – Euclidean distance between the object p from the l-th group and the gravity centre of this group; $d(\bar{\mathrm{O}}_l, \bar{\mathrm{O}}_q)$ – Euclidean distance between the gravity centres of the l-th and q-th groups ($l = 1, ..., k$; $q = 1, ..., k$; $q \neq l$) (Lula after Pociask-Karteczka, 1995).

The smaller value the selected measure has, the better the correctness of the groups created. Another measure, *MJP 28*, is used for testing the homogeneity of clusters; it is calculated from the formula (16):

$$MJP28 = \min_{p,i}\left\{d\left(0_p,0_i\right)\right\} \tag{16}$$

where: n – number of all the objects; n_l – number of objects in the l-th group; k – number of clusters; $d(0_p, 0_i)$ – Euclidean distance between the p-th and i-th objects ($l = 1, ..., k$; $p \neq i$; $p = 1, ..., n_l$; $i = 1, ..., n$).

A large homogeneity of the group (as compared with the others) is shown by the small value of *MJP 28*. The measure of cluster homogeneity *MJP 28* admits its smallest values at the levels 3 and 2 of clusters (Table 3). The measure of cluster correctness *MJP 44* has its smallest values in the case of 3 and 2 clusters (Table 3). This coefficients confirm the hypothesis that the case of grouping into 2 or 3 classes can be regarded as typologically optimal.

Due to these results, two classification variants have been accepted. In the first one, the catchments analysed form three similarity types, according to the features:

Type 1 – Biała Tarnowska, Kamienica Nawojowska, Cicha Woda, Stryszawka, Kocierzanka, Potok Kościeliski, Wisła, Biała Lądecka, Soła (both profiles), Skora (both profiles), Hoczewka, Osława, Solinka, Jasiołka, San, Łubinka, Skawa, Sękówka;

Type 2 – Czarna Hańcza, Rospuda, Krutynia, Płonia, Rega, Wda (both profiles), Wierzyca, Liwiec, Nurzec, Świder;

Type 3 – Drawa, Ełk, Omulew, Orzyc, Skrwa Prawa, Gwda, Łyna, Ina.

At the next grouping stage the catchments classified as type 2 or type 3 are joined into one type. As a result, two clearly delimited and statistically justified regions are obtained. One of them consists of catchments of mountain rivers, the other one, of catchments of lowland and lakeland rivers together.

To sum up, both classification variants – distinguishing two or three catchment types which are similar as regards their regional features – are fully justified by taxonomic similarity.

The theoretical basis of the classification method selected allow to accept the thesis that the structure of the matrix of the catchment similarity features will explain, to a large extent, the formation of floods and maximum flows changing in time.

REGIONAL FREQUENCY ANALYSIS OF MAXIMUM PROBABLE FLOWS

The catchments analysed underwent a statistical processing, aiming at the selection of the optimal probability distribution and the estimation of parameters necessary for the calculation of the probability that the maximum annual flow will be exceeded. Out of many known estimation methods the principles preferred by Ozga-Zielińska et al. 2000 (Principles of estimation of highest flows 2001) have been chosen. Statistical analysis, in accordance with the principles accepted by IMGW (*Guidelines for Flood Frequency Analysis*... 2005). Prior to the analysis, a test of the temporal homogeneity of the annual measurement sequences Q_{max} was performed. Next, the optimal selection of the probability distribution of Q_{max} was made, out of several distributions (Gamma, log Normal, Weibull and log Gamma). 24 catchments selected from three typology groups have been analysed: 14 of the mountain type and 10 of the lowland and lakeland type. The selection of the catchment depended on the length of the available sequence of annual maximum flow in 1976-2005; additionally, several sequences were rejected due to the lack of homogeneity of hydrological data.

The curves plotted from the optimal probability distribution of Q_{max} being exceeded, which best describe their formation in mountain catchments, are

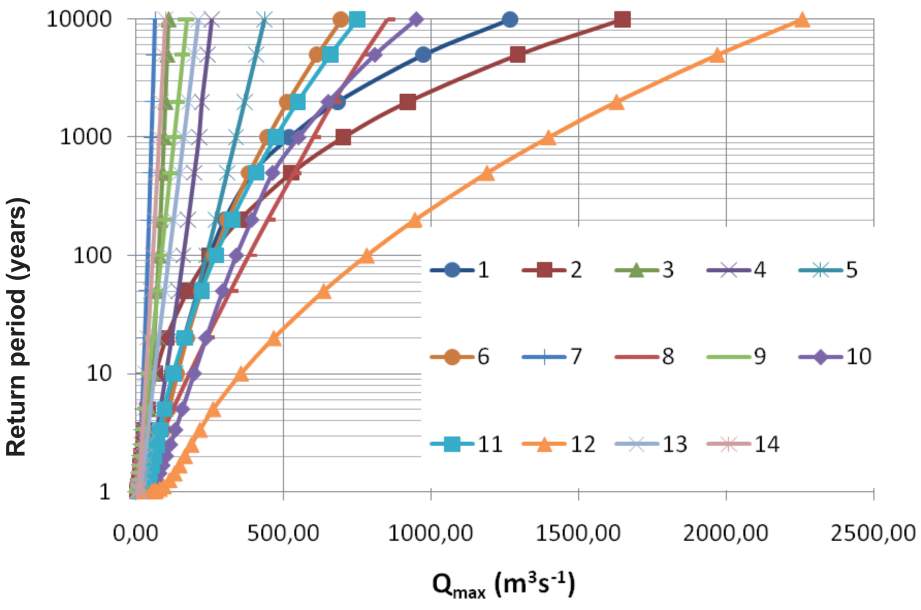

Fig. 5. Probabilty curves of annual maximum river flows in mountain catchments
1 – Biała (Biała Tarnowska) – Grybów, 2 – Biała Lądecka – Lądek Zdrój, 3 – Cicha Woda (Biały Dunajec) – Zakopane-Harenda, 4 – Hoczewka – Hoczew, 5 – Kamienica (Kamienica Nawojowska) – Nowy Sącz, 6 – Osława – Szczawne, 7 – Potok Kościeliski (Kirowa Woda) – Kościelisko-Kiry, 8 – Sękówka – Gorlice, 9 – Skawa – Jordanów, 10 – Solinka – Terka, 11 – Soła – Rajcza, 12 – Soła – Żywiec, 13 – Stryszawka – Sucha, 14 – Wisła – Wisła.

presented in fig. 5. The following rivers, closed by profiles, belong to this group: 1 – Biała Tarnowska – Grybów, 2 – Biała Lądecka – Lądek Zdrój, 3 – Cicha Woda (Biały Dunajec) – Zakopane-Harenda, 4 – Hoczewka – Hoczew, 5 – Kamienica Nawojowska – Nowy Sącz, 6 – Osława – Szczawne, 7 – Potok Kościeliski (Kirowa Woda) – Kościelisko-Kiry, 8 – Sękówka – Gorlice, 9 – Skawa – Jordanów, 10 – Solinka – Terka, 11 – Soła – Rajcza, 12 – Soła – Żywiec, 13 – Stryszawka – Sucha and 14 – Wisła (Vistula) – Wisła.

The curves of the probability distributions of the maximum annual flows in lowland and lakeland catchments (Fig. 6) comprising the second group, contain the following rivers: 1 – Brzozówka – Karpowicze, 2 – Drawa – Drawsko Pomorskie, 3 – Ełk – Ełk, 4 – Ina – Goleniów, 5 – Liwiec – Łochów, 6 – Nurzec – Boćki, 7 – Omulew – Krukowo, 8 – Rega – Trzebiatów, 9 – Skrwa (Prawa) – Parzeń and 10 – Świder – Wólka Mlądzka.

Jokiel and Tomalski (2004) cite Smith and Ward (1998) that in local mountain conditions *WWq* may reach as much as ≈ 35 thousand $dm^3\ s^{-1}\ km^{-2}$, while in lowland conditions it is almost one-third of this: ≈ 12 thousand $dm^3\ s^{-1}\ km^{-2}$. For Poland's rivers, however, in particular precipitation conditions, *WWq* $dm^3\ s^{-1}\ km^{-2}$. During the peak flow of mountain rivers, the specific discharge exceeds 1000 $dm^3\ s^{-1}\ km^{-2}$, as the above mentioned authors state.

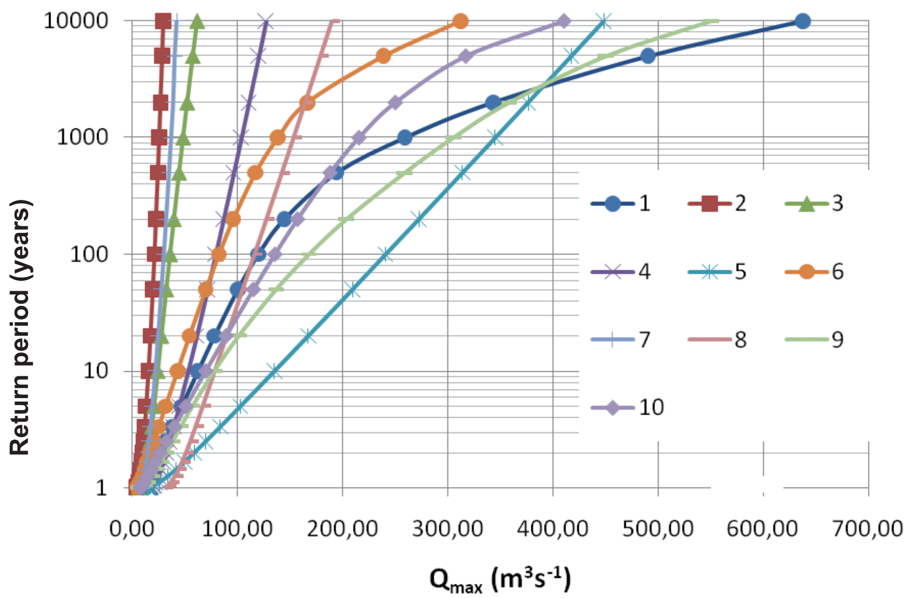

Fig. 6. Probabilty curves of annual maximum river flows in lowland and lake catchments 1 – Brzozówka – Karpowicze, 2 – Drawa – Drawsko Pomorskie, 3 – Ełk – Ełk, 4 – Ina – Goleniów, 5 – Liwiec – Łochów, 6 – Nurzec – Boćki, 7 – Omulew – Krukowo, 8 – Rega – Trzebiatów, 9 – Skrwa – Parzeń, 10 – Świder – Wólka Mlądzka.

It follows from the regional research conducted (Table 1) that a record of sorts was achieved by the Sękówka River catchment at the Gorlice profile; it reached – based on daily data – $WWq_{p1\%}$ = 3674 dm^3 s^{-1} km^{-2}. Rivers in the Sudety mountains and in uplands do not reach such high values of specific discharge, while for lowland and lakeland rivers $WWq_{p1\%} \geq 20$ dm^3/s km^2, with the Wda and Krutynia rivers reaching only ≈ 16 dm^3 s^{-1} km^{-2}. One should stress here that the specific and maximum discharges from the catchments analysed are over 200 times larger (Table 1).

The highest specific discharges in mountain catchments are of course caused by precipitation and result from the formation of a fast direct surface runoff.

One should agree with the thesis put forward by Jokiel and Tomalski (2004) that the maximum differences of the specific discharge of small (< 300 km^2) and medium (≈ 1000 km^2) catchments are definitely greater in the mountains than in lowlands or lakelands.

The value of $WWQ_{p\%}$ in 88 catchments analysed by Jokiel and Tomalski (2004) is between 946 dm^3 s^{-1} km^{-2} in the Raba river catchment at the Proszówka profile and 11.5 dm^3 s^{-1} km^{-2} in the Bystrzyca river catchment at the Sobianowice profile. The spatial irregularity is therefore only 82 times.

The relative size (33%) of the largest discharge of the catchment is represented by WWq = 40-100 dm^3 s^{-1} km^{-2} and (28%) < 40 dm^3 s^{-1} km^{-2}, out of 88 catchments considered, that is, over 60% of the population (Fig. 7).

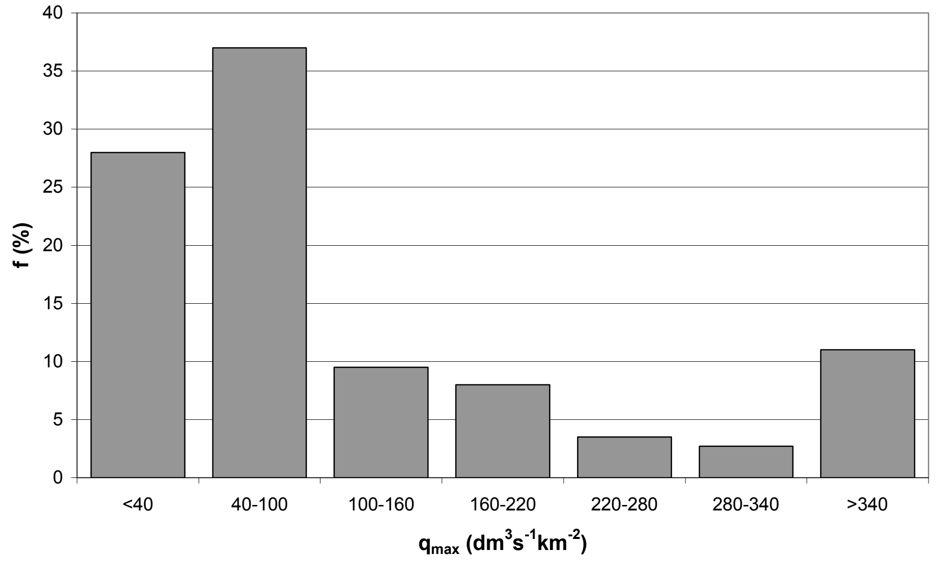

Fig. 7. Frequency in maximum specific discharge (q_{max}) (acc. Jokiel and Tomalski 2004)

One should suppose that the probable flows with recurrence period 100 years and more, predicted in mountain catchments, will be able to achieve maximum specific discharges over 500 and even up to 10 thousand $dm^3 s^{-1} km^{-2}$ (Fig. 8, markings as in Fig. 5).

Taking as the basis the estimation of the recurrence period in which the maximum specific discharge is obtained in lowland and lakeland catchments (Fig. 9, markings as in Fig. 6), we can suspect that their *WWq* will reach the value from >20 $dm^3 s^{-1} km^{-2}$ once every 10 years to 100 $dm^3 s^{-1} km^{-2}$ and even > 900 $dm^3 s^{-1} km^{-2}$ in the case of the Brzozówka, Nurzec or Świder rivers.

Lakeland catchments exhibit the greatest growth stability Wwq_r (≈ 40 $dm^3/s^{-1} km^2$), characteristic for the Drawa, Omulew and Rega rivers.

THE METHOD OF REGIONAL FREQUENCY ANALYSIS

The acceptance of the actual probable flow in an ungauged catchment under various regional conditions requires another approach, which consists in finding the relationship between the *WWQ* data from other catchments with hydrological data.

The method of regional frequency, which can be applied to this purpose, is based on the equation describing the probability curve. The parameters are found on the basis of empirical relationships and in those catchments where the basis is the average probability curve according to functional relationships between *WWQ* and physicogeographical features of the region.

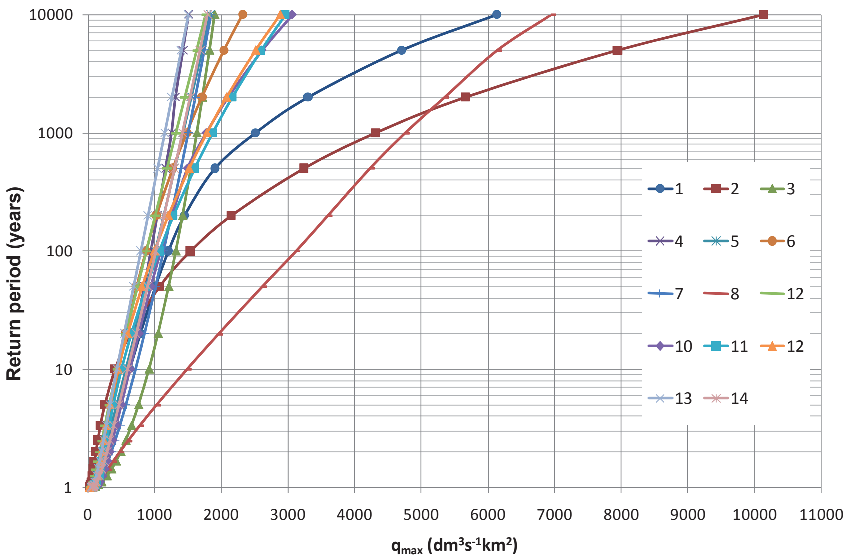

Fig. 8. Probabilty curves of the annual maximum specific discharge in mountain catchments 1 – Biała Tarnowska – Grybów, 2 – Biała Lądecka – Lądek Zdrój, 3 – Cicha Woda (Biały Dunajec) – Zakopane-Harenda, 4 – Hoczewka – Hoczew, 5 – Kamienica Nawojowska – Nowy Sącz, 6 – Osława – Szczawne, 7 – Potok Kościeliski (Kirowa Woda) – Kościelisko-Kiry, 8 – Sękówka – Gorlice, 9 – Skawa – Jordanów, 10 – Solinka – Terka, 11 – Soła – Rajcza, 12 – Soła – Żywiec, 13 – Stryszawka – Sucha oraz 14 – Wisła – Wisła.

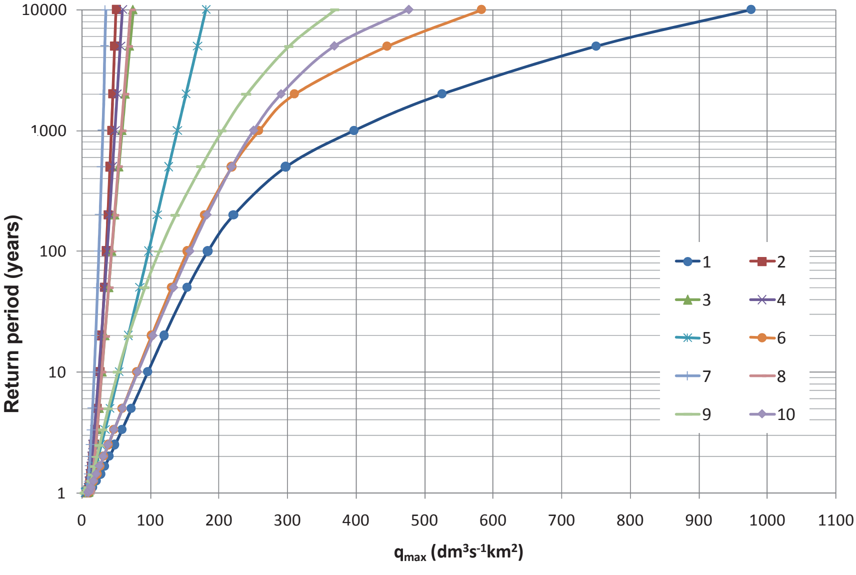

Fig. 9. Probabilty curves of the annual maximum specific discharge in lowland and lake catchments
1 – Brzozówka – Karpowicze, 2 – Drawa – Drawsko Pomorskie, 3 – Ełk – Ełk, 4 – Ina – Goleniów, 5 – Liwiec – Łochów, 6 – Nurzec – Boćki, 7 – Omulew – Krukowo, 8 – Rega – Trzebiatów, 9 – Skrwa – Parzeń i 10 – Świder – Wólka Mlądzka.

As is stressed by Ciepielowski (1976), the method of regional frequency, originating in the United States (Chow, 1964), was used to reduce the large "sample error" which occurs in the case of the analysis of the frequencies Q_{max} estimated from too short sequences from one hydrological profile. In this case, all maximum flows from various stations in the region. The usefulness of the method in two types of catchments, distinguished earlier, with measurement sequences of the same length (31 years) has been investigated.

Fleming and Franz (1971) categorise the method of regional frequency as a spatial interpolation *sui generis*. The parameter estimation was based on an optimal probability distribution of *WWQ*, chosen in advance. The parameters have been verified with respect to their homogeneity as determined by the Langbain test (Ciepielowski, 1976).

The hypothesis that the regional similarity types distinguished, expressed by means of the ratio of the values WWQ_{pr} to $WWQ_{p\%50}$ at the significance level $\lambda = 0.05$ is = 0, and thus they form a regional homogeneity.

To verify the area homogeneity, the Langbain test, using $Qmax_{p10\%}$ based on probability curve, has been applied in every catchment. The next step was the construction of the probability curve of the distributions of the coefficient $\varphi_{Rp\%}$, which denotes the ratio of the specific discharge with arbitrary probability of exceedance to the specific discharge with the probability of occurrence $p = 50\%$.

The mean value of the coefficient $\varphi_{p10\%}$ has been established; it is the ratio of the flow with probability $p = 10\%$ ($T = 10$) to the flow with probability $p = 50\%$ ($T = 2$). Next step was the determination of the limits of the dispersion of points equal to 2σ; the value σ corresponds to the parameter estimation error and is calculated for the probability distribution and estimation method by the equation (17):

$$\sigma = F/S,\ P/ \cdot \frac{Cv \cdot \varphi_{R50\%}}{\sqrt{N}} \tag{17}$$

where: C_v – variability coefficient; s – skewness coefficient; N – number of measurement years.

On the scale of probability in the coordinate system *T*, *N*, the limits of the interval σ and 2σ were marked on the map as well as the points with coordinates *T* and *N* for the catchments analysed. We assume that if the point with coordinates *T* and *N* for any catchment analysed falls between these curves, then the values from this catchment can be used for calculations (Figs. 10, 11).

The homogeneity of the region allows to determine the regional probability curve at the level of the coefficient $\varphi_{Rp\%}$ (already known). One should thus assume that the value of the runoff $Q_{maxp50\%}$ of the physicogeographical type of the catchment is equal to this sum or is very close to it; this is allowed by the procedure of the calculations of the regional probability curve.

The study on the regional homogeneity of the ratio of the maximum annual flow to the maximum high-water with the probability of exceedance

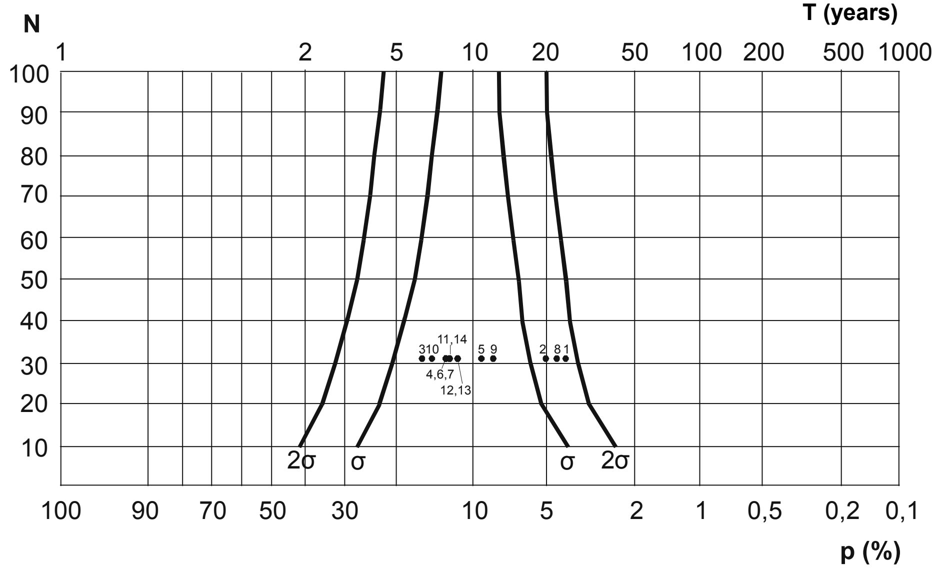

Fig. 10. Langbein test in mountain catchments (N – sample size, p – probability of the exceedance, σ – standard deviation, T – return period)

1 – Biała Tarnowska – Grybów, 2 – Biała Lądecka – Lądek Zdrój, 3 – Cicha Woda (Biały Dunajec) – Zakopane-Harenda, 4 – Hoczewka – Hoczew, 5 – Kamienica Nawojowska – Nowy Sącz, 6 – Osława – Szczawne, 7 – Potok Kościeliski (Kirowa Woda) – Kościelisko-Kiry, 8 – Sękówka – Gorlice, 9 – Skawa – Jordanów, 10 – Solinka – Terka, 11 – Soła – Rajcza, 12 – Soła – Żywiec, 13 – Stryszawka – Sucha oraz 14 – Wisła – Wisła.

50% has been performed by means of the Langbain test and method (Chow, 1967; Ciepielowski, 1976; Dąbkowski, 2006). The results obtained confirmed the regional regularity of the catchment typology performed earlier (Figs. 10 and 11). The relationships of the extreme probable values listed above vary. Therefore, the method of regional frequency analysis Q_{maxpr} and Langbain test are useful for the estimation of the formation of probable relationship of high-water to extreme annual flows in ungauged catchments in regional similarity conditions.

The correlation expressed by the Langbain test made it possible to construct regional probability curves (Fig. 12). The Gumbel distribution was applied, since it best represents the probability distribution of the extreme high-water values (Marriot, Hames, 2007; Petrow et al., 2007).

Regional maximum flow probability curves have various shapes: for mountain catchments, higher maximum flows (for the given recurrence time) are characteristic. Lowland and lakeland rivers are less prone to high-water, due to their greater retention capabilities, which in turn result from their permeability, the presence of lakes, and from other physicogeographical features. The analysis of regional frequency together with the results of the hierarchical grouping of catchments is justified in the case of analysis of peak flow magnitude and of the probability of their occurrence.

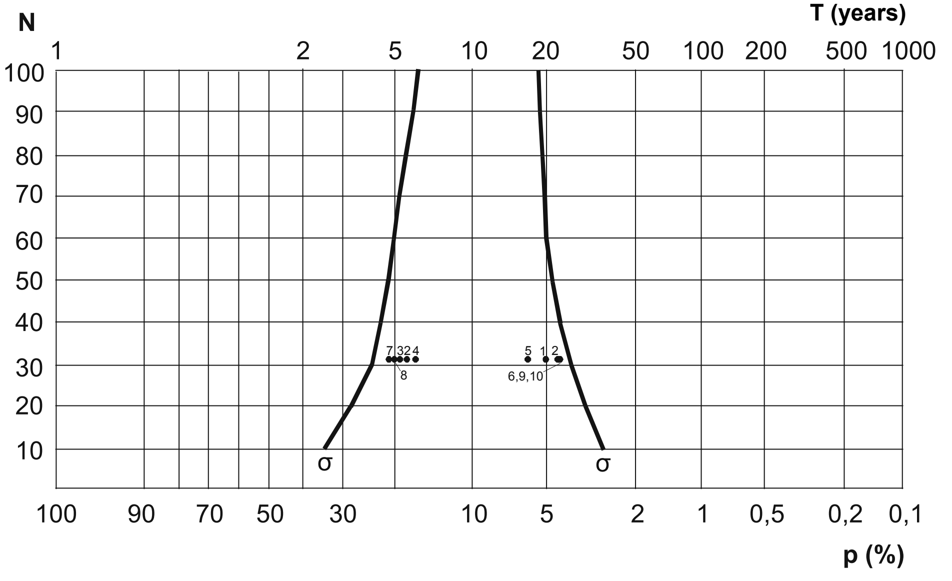

Fig. 11. Langbein test in lowland and lake catchments (N – sample size, p – probability of the exceedance, σ – standard deviation, T – return period)
1 – Brzozówka – Karpowicze, 2 – Drawa – Drawsko Pomorskie, 3 – Ełk – Ełk, 4 – Ina – Goleniów, 5 – Liwiec – Łochów, 6 – Nurzec – Boćki, 7 – Omulew – Krukowo, 8 – Rega – Trzebiatów, 9 – Skrwa – Parzeń i 10 – Świder – Wólka Mlądzka.

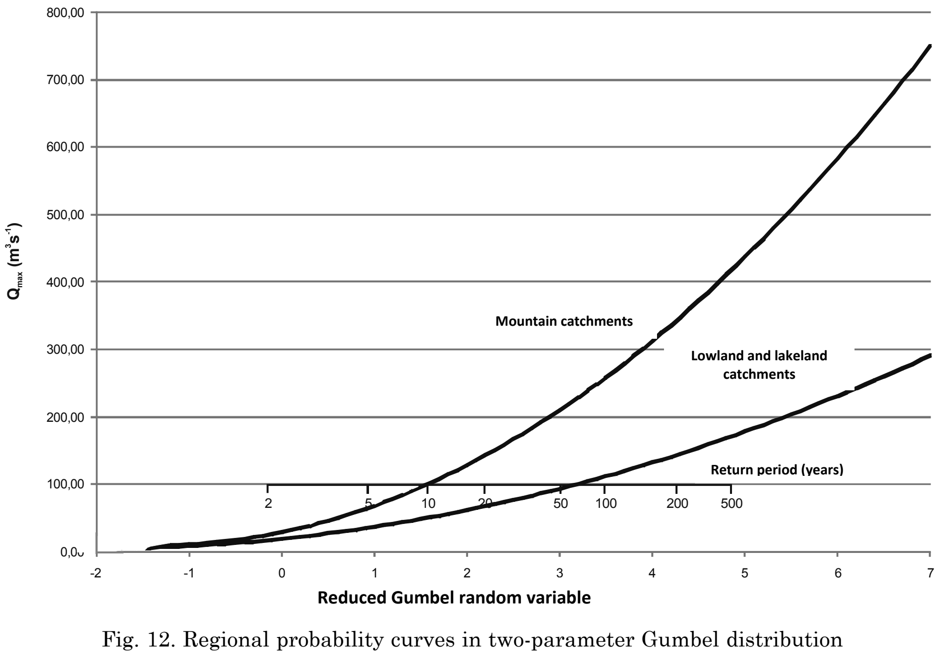

Fig. 12. Regional probability curves in two-parameter Gumbel distribution

SUMMARY

The process of catchment regionalisation – and the catchments do not always constitute a cohesive ensemble as regards their physicogeographical features and the genesis of peak flow – may be used to establish the regional maximum annual flow probability curves. Using cluster analysis, the catchments have been grouped into two regions: mountain river catchments and lowland and lakeland river catchments. The analysis showed that a correct regionalisation of catchments should result from joining their physicogeographical features with peak-flow parameters. The results obtained confirm that peak flows and floods are more probable in mountain catchments, and their recurrence period is shorter. Most often, a 100-year water is several times higher than a similar water in lowland or lakeland rivers. The determination of regional probability curves of exceedance, justified statistically, allows for spatial extrapolation of peak flows in ungauged catchments and for transfer of hydrological characteristics to an analogous catchment. Using physicogeographical features as a basis, one can approximately estimate the maximum flow with the given exceedance probability. This methods allows also to estimate the estimation of probable high-waters in rivers with only short measurement sequences, since the aggregation of data from various catchments makes it possible to increase their number. The methods of indirect estimation of probable maximum flows presented here exhibit a distinct regional similarity which depends on the rhythm of changes of physicogeographical features of the catchment.

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