GEOGRAPHY AND TOURISM, Vol. 5, No. 2 (2017), 17-26, Semi-Annual Journal
eISSN 2449-9706, ISSN 2353-4524, DOI: 10.5281/zenodo.1118158

Edmund Tomaszewski
University of Łódź, Faculty of Geographical Sciences, Department of Hydrology and Water Management,
e-mail: edtom@uni.lodz.pl

Seasonal concentration time of hydrological drought in Poland

Abstract: The time of hydrological drought concentration was estimated based on Markham's indices. The research material consisted of a series of daily discharges from the period of 1985-2014 obtained from 79 cross sections of stream gauges distributed along rivers in Poland. In the first stage of the research, low-flow episodes were identified at the threshold level of Q70%, derived from the flow duration curve. Drought streamflow deficit volumes were calculated and assigned to monthly intervals. On this basis, the hydrological drought concentration time index and the hydrological drought seasonality index were assessed for particular years and for the whole study period. Spatial and temporal analysis was carried out on both characteristics, paying particular attention to a number of factors determining the investigated phenomenon and the long-term stability of hydrological drought concentration time.

Keywords: hydrological extremes, river low-flow periods, streamflow deficit

1. Introduction

Hydrological drought is the most severe effect of long-term alimentation deficits, caused by precipitation shortage and snow retention. It occurs as a result of meteorological and agricultural drought, the effects of which are usually intensified by increased evapotranspiration and lead to significant depletion of groundwater resources in the hydrologically active zone (groundwater low-flow) and in hydraulically connected river beds (surface water low-flow). Thus, the streamflow drought that occurs at the end of the chain of events (adverse in terms of the water management) can be considered as a reliable indicator of hydrological drought development (Tokarczyk, 2010; Tomaszewski, 2012). The low-flow is commonly referred to as a period of low flows (water levels) in a river or flows during prolonged dry weather (Dębski, 1970; Smakhtin 2001). A more precise definition of this phenomenon depends on research approaches or practical objectives of a given analysis. The most common methodology described in the literature of the subject is based on the determination of a threshold discharge, according to which low-flow periods are characterised by a lowering of flows below the accepted truncation level. According to this research approach, the streamflow deficit volume in the period when it is lower than the threshold flow becomes the primary parameter of the identified phenomenon, along with a low-flow episode duration (Fig. 1). The main disadvantage of this method is the possibility of applying a variety of criteria for a threshold flow (e.g. the main characteristic flows of the 2nd degree, percentile flows identified according to the flow duration curve or conventional flows), while the advantage is the possibility of interpreting and comparing the results related to a fixed-time criterion.

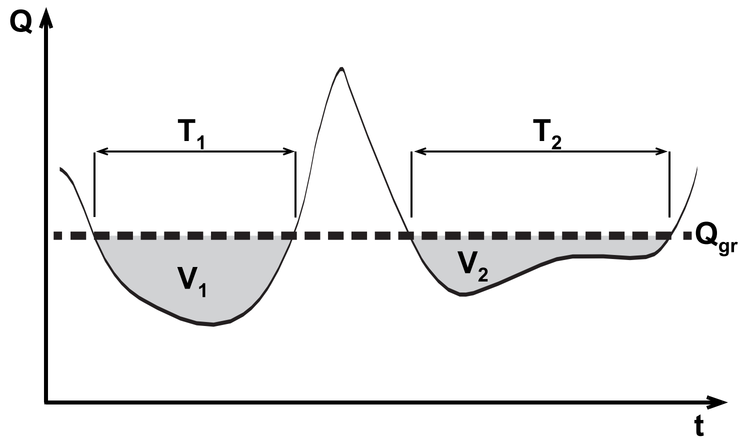

Figure 1. Basic parameters of low-flow
V – streamflow deficit volume, T – low-flow duration, Q_{gr} – threshold level

On the one hand, the low-flow as a hydrological extreme is determined by environmental conditions prevailing on a local and regional scale, while on the other hand it can be significantly modified by water management practices. Furthermore, the temporal discontinuity and high randomness of its occurrence makes the analysis conducted at an over regional scale much more difficult. Basically no other reports on seasonal patterns in the occurrence of river low-flows across the country have been published since the maps by Z. Mikulski (1963) and A. Stachý et al. (1979). And yet the hydroclimatic conditions that determine this phenomenon and the water management practices, especially those related to drought mitigation strategies, have significantly changed over the past few decades, which is confirmed by a large number of studies conducted at a regional scale or within individual catchments. This paper presents characteristics that enable a synthetic (two-parameter) approach to seasonal patterns of streamflow drought deficits. Based on these characteristics, it is possible to compare geographic regions in terms of hydrological drought concentration time and its role in the formation of streamflow low-flow regimes.

2. Research method and material

The severity of hydrological drought primarily depends on hydrometeorological conditions of the period preceding its occurrence. The shortage of water resources may be determined by seasonal anomalies related to lack of groundwater recharge in a typical recharge season, or long-term anomalies induced by e.g. a series of dry years. Both groups of factors randomly overlap and are difficult to separate, hence the incidence and intensity of droughts and low-flow periods are very irregular and difficult to predict.

Large irregularities in the occurrence of streamflow drought deficits significantly impede the seasonal analysis based on time series analysed in a monthly step. The solution to this problem may be the characteristics describing the seasonal variability in a comprehensive way. The approach based on angular measures introduced in the literature by C.G. Markham (1970) can be used to identify the extent of irregularities in the annual streamflow drought deficits. In the original version, the measures were used to analyse the seasonal variability in the precipitation in the USA, but after some methodological changes, two measures of seasonality were proposed: the index of seasonality (IS) and the index of concentration time (ICT) of hydrological drought.

Both measures are based on the assumption that the monthly streamflow drought deficit volume is represented by vector (r_i), the length of which is proportional to the volume of that deficit and the angle of inclination (α_i) depends on the mid-month position in relation to the beginning of the hydrological year:

$$\alpha_i = \frac{360 \cdot S}{365},$$

where: S – the number of days between the beginning of the hydrological year and the middle of a given month

As a result, 12 vectors are obtained, for which the resultant vector R is calculated with the module |R| and the direction ω (Fig. 2). Based on the quotient of the resulting vector |R| length and the total length of partial vectors $|r_i|$, the index of seasonality IS is calculated as follows:

$$IS = \frac{|R|}{\sum_{i=1}^{12} |r_i|} \cdot 100\%$$

The derived measure takes values within the range of 0-100%, and the seasonality level of the hydrological drought increases with the increasing value. It is worth noting that the value equal to 0% may not only reflect the perfect regularity in the streamflow drought deficit throughout the year, but also a situation when hydrological drought is concentrated in two opposing months only (e.g. November and May). Both cases are extreme and theoretical, but they show the necessity for careful interpretation of the results. The inclination angle of the resulting vector R (ω) is an estimator of the hydrological drought seasonal concentration time (Fig. 2), and the index of drought concentration time (ICT) is computed according to the formula:

$$ICT = \mathrm{arctg}\left(\frac{\sum_{i=1}^{12} |r_i| \cos\alpha_i}{\sum_{i=1}^{12} |r_i| \sin\alpha_i}\right) \cdot \frac{365}{360}$$

The ICT indicates the time of streamflow drought deficit concentration (in days in relation to the beginning of the hydrological year), but it should not be equated with the occurrence of hydrological drought of the maximum intensity or the total streamflow deficit. Combined with the seasonality index, the ICT assesses not only the hydrological drought seasonal concentration time but also its severity, which is important in the assessment of the stream low-flow regime.

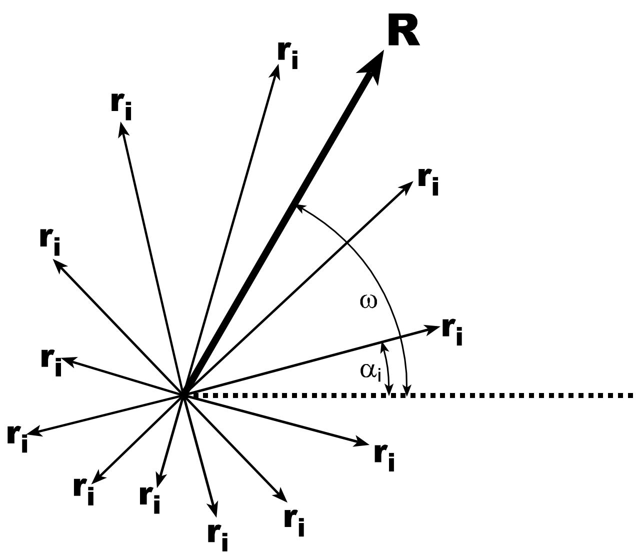

Figure 2. Construction of Markham's seasonality measures

r_i – vector representing the streamflow drought deficit in month *i*, R – the resulting vector for vectors r_i, α_i – angle representing the mid-month position, ω – angle indicating the time of hydrological drought concentration in relation to the beginning of the hydrological year.

Both measures bring a significant load of information on the seasonal features of the river regime and they were used in previous researches on the groundwater flow (Tomaszewski, 2001; 2007), low flows (Bartnik, 2005), total runoff (Jokiel and Bartnik, 2001; Bartnik, Tomaszewski 2006), and the groundwater level (Tomalski, 2011) conducted in Poland. Interesting results have also been obtained with respect to hydrological drought seasonality in catchments of central Poland (Tomaszewski, 2012).

The study covered 79 stream gauge stations in Poland (Table 1). Their location reflects a full spectrum of river regimes observed in Poland as well as a variety of physico-geographical conditions affecting the low flows formation and their deficits. The observation period of 1985-2014 was used in the analyses. The duration of the period meets a criterion of at least 30 years specified in the literature as a minimum duration of a representative series for hydrological analyses and provides an up-to-date picture of the studied phenomenon.

The calculation was based on the series of daily discharges prepared and provided by IMGW-PIB (Institute of Meteorology and Water Management-National Research Institute). A flow corresponding to the 70th percentile of the flow duration curve was assumed as a threshold value (Fig. 1 – Q_{gr}). Streamflow drought deficits were estimated in the identified low-flow periods and assigned to corresponding months. At a later stage, the index of hydrological drought concentration time (ICT) and the hydrological drought seasonality index (IS) were calculated for every year as well as for the whole period (Fig. 3).

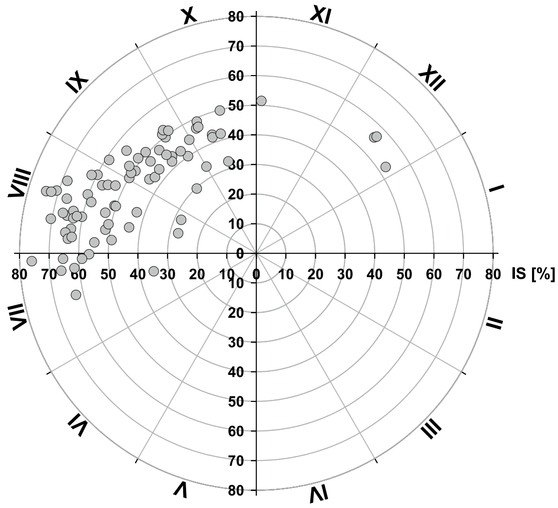

Figure 3. Position of vector tips representing the seasonality index and the index of hydrological drought concentration time calculated for the period of 1985-2014.

Table 1. Selected characteristics of hydrological drought seasonality (1985-2014)

No.	River	Stream gauge	A [km²]	ICT (data)	C [%]	IS [%]
1	Oder	Racibórz-Miedonia	6744.0	9-09	23.3	51.2
2	Oder	Ścinawa	29583.8	19-09	34.5	43.3
3	Oder	Słubice	53382.0	8-09	24.1	55.9
4	Oder	Gozdowice	109729.1	2-09	34.5	58.8
5	Olza	Cieszyn	453.5	17-09	30.0	47.8
6	Mała Panew	Staniszcze Wielkie	1107.4	4-09	23.3	49.4
7	Eastern Neisse	Kłodzko	1084.0	25-09	16.7	40.1
8	Eastern Neisse	Skorogoszcz	4514.5	13-10	17.2	32.4
9	Oława	Oława	956.7	25-08	24.1	27.8
10	Ślęża	Borów	547.2	31-08	45.8	49.9
11	Bystrzyca	Jarnołtów	1709.7	17-09	28.6	29.7
12	Strzegomka	Łazany	356.1	29-09	27.6	44.5
13	Widawa	Zbytowa	721.0	8-08	50.0	63.1
14	Kaczawa	Dunino	774.0	17-09	13.3	42.1
15	Barycz	Osetno	4579.3	6-08	40.0	49.1
16	Bóbr	Wojanów	535.4	12-09	24.1	50.6
17	Bóbr	Żagań	4254.3	17-09	20.7	45.0
18	Kwisa	Mirsk	185.6	19-08	20.0	42.7
19	Kwisa	Nowogrodziec	735.5	4-09	27.6	43.9

20	Lusatian Neisse	Gubin	3973.6	27-08	31.0	59.8
21	Warta	Działoszyn	4088.5	24-08	44.8	56.9
22	Warta	Poznań (Most Rocha)	25910.9	19-08	50.0	50.5
23	Warta	Gorzów Wielkopolski	52404.3	20-08	46.4	60.3
24	Liswarta	Kule	1557.0	4-08	38.5	54.8
25	Prosna	Bogusław	4303.5	12-08	62.1	65.2
26	Noteć	Pakość	2356.2	23-08	31.3	53.4
27	Noteć	Nowe Drezdenko	15970.1	13-08	53.3	63.4
28	Gwda	Piła	4704.3	26-08	46.7	61.6
29	Drawa	Drawiny	3287.0	17-08	63.3	74.0
30	Ina	Goleniów	2162.7	11-08	54.2	62.9
31	Rega	Trzebiatów	2628.0	7-08	50.0	64.8
32	Parsęta	Bardy	2955.2	12-08	65.5	60.2
33	Wieprza	Stary Kraków	1518.7	30-07	43.3	65.3
34	Słupia	Słupsk	1450.4	31-07	36.7	56.5
35	Łupawa	Smołdzino	804.6	26-07	31.0	61.6
36	Łeba	Cecenowo	1120.2	26-07	31.0	66.1
37	Reda	Wejherowo	395.2	18-07	50.0	62.5
38	Vistula	Nowy Bieruń	1747.7	21-07	33.3	35.2
39	Vistula	Sandomierz	31846.5	16-10	36.7	49.7
40	Vistula	Warszawa - Nadwilanówka	84540.0	6-10	16.7	48.8
41	Vistula	Kępa Polska	168956.1	22-09	43.3	49.7
42	Vistula	Tczew	194376.0	22-09	36.7	51.2
43	Przemsza	Jeleń	1995.9	11-09	35.0	47.3
44	Soła	Oświęcim	1386.0	30-09	26.7	33.8
45	Skawa	Wadowice	835.4	10-10	30.0	42.7
46	Raba	Proszówki	1470.4	9-10	15.4	41.8
47	Dunajec	Nowy Targ - Kowaniec	681.1	27-12	40.0	52.5
48	Dunajec	Nowy Sącz	4341.0	16-12	33.3	55.8
49	Dunajec	Żabno	6735.0	1-11	16.7	51.4
50	Poprad	Stary Sącz	2071.0	16-12	40.0	56.6
51	Biała	Koszyce Wielkie	956.9	4-10	23.3	46.8
52	Nida	Pińczów	3352.5	25-08	41.4	55.2
53	Wisłoka	Mielec	3893.0	5-10	13.3	46.9
54	San	Lesko	1614.0	14-10	27.6	42.1
55	San	Radomyśl	16823.8	23-09	37.9	52.1
56	Wisłok	Tryńcza	3516.0	24-09	50.0	50.9
57	Wieprz	Krasnystaw	3001.0	15-08	30.8	27.2
58	Wieprz	Kośmin	10230.6	12-08	56.0	43.8
59	Pilica	Przedbórz	2535.9	19-08	46.4	50.0
60	Pilica	Białobrzegi	8664.2	18-08	67.9	58.3
61	Narew	Suraż	3376.5	26-08	35.7	52.8
62	Narew	Zambski Kościelne	27782.3	21-08	44.8	68.3
63	Supraśl	Fasty	1816.6	29-07	23.3	58.9
64	Biebrza	Burzyn	6900.4	17-08	57.1	66.6
65	Pisa	Dobrylas	4061.2	7-09	24.0	42.8

66	Orzyc	Maków Mazowiecki	1948.1	12-08	40.0	66.7
67	Bug	Włodawa	14410.0	23-09	32.1	42.9
68	Bug	Wyszków	39119.4	12-09	37.9	46.8
69	Krzna	Malowa Góra	3127.7	12-08	46.7	61.9
70	Liwiec	Łochów	2465.5	5-08	53.3	63.8
71	Wkra	Borkowo	5111.0	10-08	51.7	70.3
72	Drwęca	Elgiszewo	4959.4	18-08	51.9	70.7
73	Brda	Tuchola	2462.2	29-07	53.3	75.9
74	Radunia	Juszkowo	762.5	9-08	43.3	51.6
75	Pasłęka	Łozy	2015.5	11-08	37.9	50.9
76	Łyna	Sępopol	3647.2	15-08	43.3	52.8
77	Guber	Prosna	1567.8	4-09	20.0	52.0
78	Węgorapa	Mieduniszki	1580.0	11-09	30.0	43.3
79	Czarna Hańcza	Jałowy Róg	832.7	17-08	53.3	72.3

A – catchment area, ICT – the index of hydrological drought concentration time, C – the coefficient of concentration time frequency, IS – the index of hydrological drought seasonality

3. Seasonal concentration time

The average seasonal concentration time of hydrological drought in Poland falls on 23 August (Fig. 4A). Noteworthy is a group of outliers, connected with the autumn-winter concentration time in the catchments of the Tatras and the Western Beskids (Table 1). The range of the described parameter in the remaining part of the country is relatively narrow, and half of the drainage basins covered by this study (interquartile range IR) experiences the hydrological drought concentration between 11 August and 17 September. The presented distribution of ICT values indicates that the main factors determining the occurrence of streamflow drought deficits in Poland include warm half-year rainfall deficiencies and the process of evapotranspiration accompanying the growing season. Low-flows in the cold season, caused by the accumulation of water resources in the snow cover as well as by frost penetration of river beds, occur in a limited extent, both in quantitative and spatial terms.

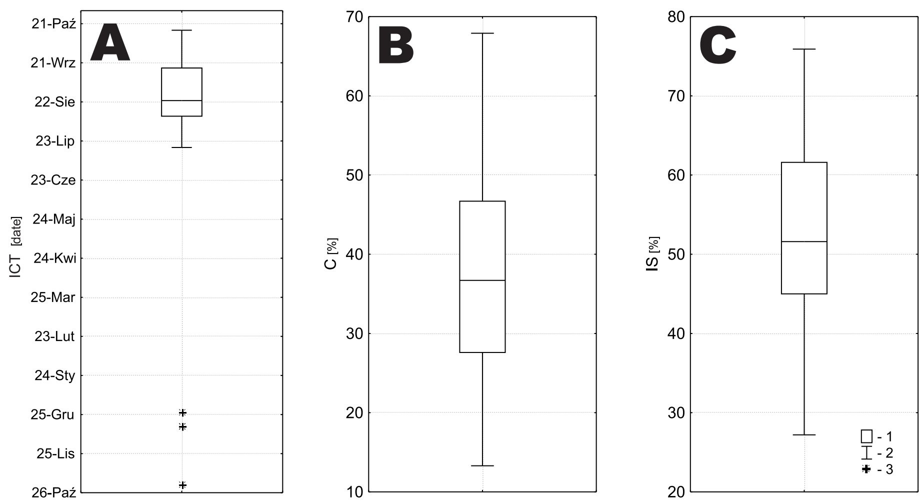

Figure 4. Distribution of the hydrological drought concentration time index (ICT), the concentration frequency coefficient (C) and the hydrological drought seasonality index (IS)

1 – the range of dispersion restricted by the first and third quartile; the median inside; 2 – the range of non--outliers within one interquartile deviation; 4 – extreme values above one interquartile deviation.

Spatial differentiation in seasonal concentration time of hydrological drought shows a clear spatial pattern (Fig. 5). The December concentration of hydrological drought occurs in the upper reaches of the Dunajec River drainage basin. It is worth emphasizing that the time of concentration does not indicate the date of the most severe hydrological drought but is a resultant (in a weighted average sense) affected by the timing and the low-flow depth observed throughout the year. One could thus argue that winter low-flows in the upper Dunajec drainage basin prevail over streamflow drought deficits occurring in the warm season. The Dunajec river itself carries this feature of streamflow seasonality up to the estuary, but alimentation of flow of subsequent tributaries shift the time of concentration in its lower reaches till early November. Thus, the increased contribution of summer streamflow drought deficits causes that the time of hydrological drought concentration in most Carpathian tributaries of the Vistula River is shifted towards the first half of October. The low flow regime of the upper Vistula River seems to be mostly dependent on the Carpathian rivers, because the concentration of hydrological drought, according to the water-level gauge in Sandomierz, occurs in the first half of October. The results obtained for the source section of the Vistula River deserve a few words of comment. The estimated time of concentration in July results from the influence of the Goczałkowice Reservoir, where municipal water resources are replenished mainly in spring and during summer flood waves. Consequently, during periods of a typical increased flow, low-flows are observed below the dam, which significantly modifies the low flow regime in this section of the river (the analysis included data from the water-level gauge in Nowy Bieruń – Table 1).

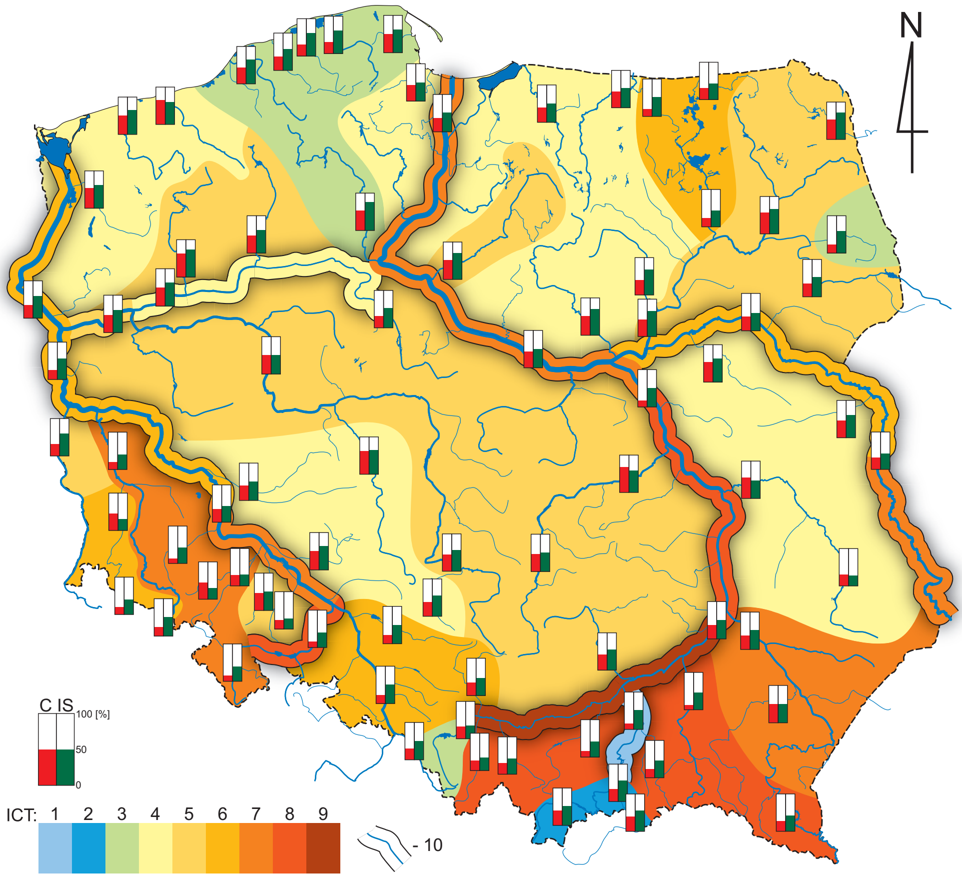

Figure 5. Seasonal concentration time of hydrological drought in Poland (1985-2014) (after e. Tomaszewski 2017, modified)

The index of hydrological drought concentration: 1 – 1-15 XI, 2 – 16-31 XII, 3 – 16-31 VII, 4 – 1-15 VIII, 5 – 16-31 VIII, 6 – 1-15 IX, 7 – 16-30 IX, 8 – 1-15 X, 9 – 16-31 X; 10 – changes in ICT in the major transit rivers (out of the map's scale); the colour of the band filling consistent with periods: 1-9; C – the coefficient of concentration time frequency, IS – the hydrological drought seasonality index.

The regularities outlined above are also observed in the Sudeten streams. The major difference consists in the shift of the average hydrological drought concentration time in relation to the Carpathians by about half a month. Rivers that originate in the Kłodzko Valley, the Karkonosze and Kaczawskie Mountains are characterised by the concentration time in the second half of September, indicating a higher proportion of winter low-flows compared to other watercourses in this region. The impact of Otmuchów and Nyskie lakes is clearly reflected in the delayed concentration time in the Eastern Neisse River. This strong impact is transmitted to the Oder River.

The August hydrological drought concentration time prevails in most of the upland and lowland catchments. Watersheds whose water resources are slightly smaller compared to other catchments are characterised by ICT in the first half of August. Those are: right-hand tributaries of the middle Oder River, left-sided tributaries of the upper and middle reaches of the Warta River, watercourses of the region between the Vistula and the Bug River as well as certain drainage basins of lake districts. In these catchments, the higher recession rate of water resources results in a slightly earlier time of hydrological drought concentration. In river basins with a high lake percentage and large contribution of lakes with through- and outflowing streams, the time of concentration occurs slightly later (e.g. catchments of the Pisa, the Drwęca, the Gwda, the Drawa, the upper Noteć River). In the rivers of Przymorze, the concentration time of hydrological drought occurs earlier in the eastern part of this region, which is directly attributable to the earlier occurrence of the total runoff concentration time (Bogdanowicz 2009).

It is worth noting that the low flow regime of some transit rivers show allochthonous features. The hydrological drought concentration time in the upper Vistula, below the Goczałkowice Reservoir, is under the predominant influence of the Carpathian tributaries, because the ICT occurs there on 16 October. After alimentation of the San waters, the concentration time of hydrological drought occurs 10 days earlier, and after merging with the Bug and Narew waters, it occurs on 22 September, which continues up to the estuary. As it can be easily observed, the difference in the concentration time between the lower Vistula and its autochthonous tributaries may exceed even 2 months. Slightly smaller differences are observed for the Oder and the Bug, which show the gradual influence of subsequent tributaries, but preserve the low flow regime up to the estuary. An interesting phenomenon occurred in the middle and lower Noteć River which, despite "inheriting" the low-flows from the upper part of the river basin and tributaries with a relatively high lake percentage, responds with the earlier hydrological drought concentration time, probably due to the small water resources and extensive use of waters from this part of the drainage basin.

4. Stability and seasonality level of the concentration time

The average time of hydrological drought concentration and its variability is an interesting characteristic providing additional valuable information on the streamflow regime. The coefficient of drought concentration frequency (C) is assumed in this paper as an estimator of the stability of this feature of the river regime. The measure indicates the percentage of years during which the concentration occurred in a month characteristic of the average time of concentration in relation to the total number of years in the studied multiannual period (Table 1). The mean value of the frequency coefficient in Poland was just over 35% (Fig. 4B). This means that on average every 3 years the hydrological drought concentration occurs in a month typical of the multiannual period. It is worth noting that the coefficient of frequency was in the range of 28-47% in half of the analysed cases, while in only 18 surveyed catchment areas the concentration occurred in a typical month every second year or more often.

The time of concentration is least stable in mountain rivers whose flow regimes are characterised by genetically different summer and winter low-flows (Fig. 5). In catchments where hydrological drought concentration time occurs in August and September, the level of stabilization is much higher and results from greater homogeneity of factors that determine the development of streamflow drought deficits. It is worth noting, however, that in many lake and upland catchments with a high contribution of groundwater alimentation, the long-term stability of the concentration time is slightly lower, because these factors may significantly mitigate the effects of hydrometeorological impulses. In transit rivers, the frequency coefficient decreases when low-flows of tributaries are not synchronous in relation to low-flows of the main river. This situation is observed on the Vistula River after the discharge of the San waters and on the Oder after merging with the Bóbr and the Lusatian Neisse, and further with the Warta.

Irregularity of streamflow drought deficits distribution during a year is described by the hydrological drought seasonality index (IS). The mean value of this characteristic for the area of Poland was 51.6% (Fig. 4C). For half of the analysed cases, the IS ranges from 45 to 61%, and the extreme values of the distribution are 27.2% (Wieprz–Krasnystaw) and 75.9% (the Brda River–Tuchola) – Table 1. Low values of the hydrological drought seasonality index are characteristic of catchment areas with a high and stable base flow index, ensuring the regular distribution of groundwater alimentation throughout the seasons (e.g. the Wieprz, the Bystrzyca, the Oława, the upper Eastern Neisse, the Kaczawa; Fig. 5). A similar effect can be observed in rivers below large dam reservoirs (e.g. the lower Eastern Neisse, the upper Vistula River, the Soła), where mitigation of drought consequences is reflected in the low flow regime. Values below the mean IS index are determined in mountain catchment areas, where winter streamflow drought deficits are equally important as summer deficits. The seasonality level of hydrological drought in the lowland area is high or very high due to the high similarity of factors determining the formation and depth of the low-flows.

5. Conclusions

As evidenced by the performed analyses, both the time and the concentration level of hydrological drought in Poland show significant and multidirectional changes. In mountain rivers, the significant role in the low flow regime is played by genetically different summer and winter low-flows (ICT – IX-XII), while summer deficits prevail in the rest of the country (ICT – VII-IX). In addition to hydrometeorological conditions, the seasonal distribution of streamflow drought deficits is determined by local factors associated with the abundance of water resources and the rate of exchange of resources in the hydrologically active zone as well as some water management practices. Large transit rivers gradually change their low flow regime along with the discharge of subsequent tributaries, but they preserve the specific characteristics of their hydrological regime up to the estuary. Allochthonous features of the low flow regime, inherited from the upper part of drainage basins and larger tributaries are observed for: the Vistula River, the Oder River, the Bug, the Noteć, the Eastern Neisse, the Dunajec. It is worth noting, however, that the high seasonality level of hydrological drought occurs when the average concentration time coincides with summer months (Fig. 3). As the ICT moves towards the autumn months, the index of seasonality decreases, because low-flows of the cold half-years are becoming increasingly important.

References

Bartnik A., 2005. Low flow in Poland. Acta Geographica Lodziensia 91, Łódzkie Towarzystwo Naukowe, Łódź [In Polish with English abstract].

Bartnik A., Tomaszewski E., 2006. Zastosowanie indeksu pory koncentracji do oceny podatności reżimu rzecznego na formowanie przepływów ekstremalnych w zlewniach nizinnych. [In:] Kostrzewski A., Czerniawska J. (Eds.), Przemiany środowiska geograficznego Polski północno-zachodniej. Bogucki Wydawnictwo Naukowe, Poznań, 137–144 [In Polish].

Bogdanowicz R., 2009. Water resources of coastal rivers and their variability. [In:] Bogdanowicz R., Fac-Beneda J. (Eds.) Water resources and water protection. Water and matter cycling in river basins. Fundacja Rozwoju Uniwersytetu Gdańskiego, Gdańsk, 47–62 [In Polish with English abstract].

Dębski K., 1970. Hydrologia. Arkady, Warszawa [In Polish].

Jokiel P., Bartnik A., 2001. Changes in seasonal distribution of outflow in central Poland during 1951-1988. Wiadomości IMGW 2, 3–17 [In Polish with English abstract].

Markham C.G., 1970. Seasonality of Precipitation in The United States. Annals of the Association of American Geographers 60(3), 593–597.

Mikulski Z., 1963. Zarys hydrografii Polski. PWN, Warszawa [In Polish].

Smakhtin V.U., 2001. Low flow hydrology: a review. Journal of Hydrology 240, 147–186.

Stachý J., Biernat B., Dobrzyńska I., 1979. Odpływ rzek polskich w latach 1951–1970. Materiały Badawcze IMGW, Seria Specjalna 6, Wydawnictwo IMGW, Warszawa [In Polish].

Tokarczyk T., 2010. Low flow as an indicator of hydrological drought). Monografie IMGW, Wydawnictwo IMGW, Warszawa [In Polish with English abstract].

Tomalski P., 2011. The dynamics of shallow groundwater resources in the Łódź region and neighbouring areas. Acta Geographica Lodziensia 97, Łódzkie Towarzystwo Naukowe, Łódź [In Polish with English abstract].

Tomaszewski E., 2001. Seasonal changes of groundwater flow in Poland in the period 1971-1990. Acta Geographica Lodziensia 79, Łódzkie Towarzystwo Naukowe, Łódź [In Polish with English abstract].

Tomaszewski E., 2007. Time concentration of the groundwater runoff in central Poland). [In:] Michalczyk Z. (Eds.), Obieg wody w środowisku naturalnym i przekształconym. Wydawnictwo UMCS, Lublin, 537–547 [In Polish with English abstract].

Tomaszewski E., 2012. Multiannual and seasonal dynamics of low-flows in rivers of central Poland. Wydawnictwo Uniwerystetu Łódzkiego [In Polish with English abstract].

Tomaszewski E., 2017. Niżówki i susze. [In:] Jokiel P., Marszelewski W., Pociask-Karteczka J. (Eds.), Hydrologia Polski. Wydawnictwo Naukowe PWN, Warszawa [In Polish].