

## DROUGHT STREAMFLOW DEFICITS ASSESSMENT, APPLYING CONSTANT AND VARIABLE THRESHOLD LEVELS, AS ILLUSTRATED WITH THE EXAMPLE OF SELECTED CATCHMENTS IN THE VISTULA RIVER BASIN

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### ABSTRACT

In the present study, the author has assessed drought streamflow deficits, and the characteristics of the low flows at a constant and variable (monthly) low-flow threshold. The low-flow truncation level was identified based on the 70th percentile from the flow duration curve ( $Q_{70\%}$ ). The flow at ordinate 95% was assumed to be the threshold for the deep low-flow. Thirteen catchments in the Vistula basin, varying in size, river regime, and physico-geographical conditions, were selected for the study. The input data was series of daily discharge from the period 1951–2016, made available by IMGW-PIB (Polish Institute of Meteorology and Water Management – National Research Institute). Analyses were conducted for drought streamflow deficit volume in absolute and relative values, low-flow duration and deficits contributing to severe low-flows were calculated for temporal scales of months and years. Comparison of the obtained results led to the determination of the basic factors affecting the formation of drought streamflow deficits, and the indication of restrictions when applying fixed and variable criteria for identifying river low-flows.

**Keywords:** low flows regime, low-flow threshold level, hydrological drought, the Vistula river basin

### INTRODUCTION

Information on water resources shaped under hydrological drought conditions is not only of key importance to carrying out water management activities, but it also significantly supports the analysis of hydrological processes, their modelling, and a range of issues related to environmental protection. To date, the approaches to identifying river low-flows, indicating the level of hydrological drought development, were mostly based on the assumption that the threshold value is fixed, meaning the constant upper limit for the development of low flows. The application of a fixed reference level facilitates the analysis of the continuity

of the process, and is a very useful tool supporting the assessment of the operation of water management devices and facilities dependent on river flow variability (for instance, water intakes, hydroelectric plants, etc.). The results of the analyses of this type are also very useful in water management planning.

It should be noticed however, that in the hydrological system, deficit periods, similarly to any other phenomena, are forming in a dynamic way. Therefore, the adoption of a constant threshold value does not fully reflect the response of the catchment active exchange zone to alimentation shortages. Already Dębski (1952) noticed that particularly troublesome low-flows occur when water deficits happen in typical resource-feed pe-

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riods. Therefore, their definition should refer to those features of the flow regime, which will facilitate the identification and valorisation of periods with significant disturbances in the water balance structure. Taking this postulate under consideration requires the use of a threshold value of the flow, that is variable in time, but it is also repeatable in the annual cycle, which shall provide the basis for identifying the low-flow.

## STUDY METHOD

In the present study, the low-flows were identified on the basis of the statistical criterion, in which the low-flow is considered to be the period with discharges below the limit value, adopted on the basis of the characteristic flow (Ozga–Zielińska 1990). The threshold value was the flow corresponding to the 70th percentile from the flow duration curve, determined for the entire multiannual period (Hisdal et al. 2004). The author has also made an estimation of deep low-flows, occurring due to the depletion of seasonal resources of the catchment active exchange zone, and the transition to the alimentation of the channel from aquifers characterized by a long-term rhythm only. The threshold value of such low-flow periods corresponded to the 95th percentile (Tomaszewski 2012).

Further calculations were carried out in two variants. In the first one, constant truncation level for the entire multiannual period were determined. In the second instance, threshold flows were estimated separately for each of the 12 months of the hydrological year (see: Fig. 1). In each case, the volume of the drought streamflow deficit, and the number of days with low flow were calculated in the consecutive months and years, which made it possible to compare the quantity and dynamics of drought streamflow deficits formation at constant and variable low-flow threshold.

Studies on the application of changeable in time low-flow threshold discharge, were already conducted in the second half of twentieth century. They were based on the separating the seasons with different genetic determinants of the river flow deficits, associated with precipitation shortage and evapotranspiration in the warm season, as well as deficits resulting from snow retention and freezing of channels in the cold season. As a result of the conducted analyses, an arbitrary division of the year was made into half-

years, or any two other seasons of different length, resulting from the temperature distribution, depending on the catchment location in a given type of temperate climate (Tlačka 1979; Laaha 2002; Laaha and Blöschl 2006; Pfister et al. 2006).

Low-flow threshold level, variable in a monthly or daily step, was previously considered mainly in the theoretical sphere, and in terms of applications in the probability distribution analyses of drought streamflow deficit occurrence (Stahl 2001; Hisdal 2009). The exception is the operational use of threshold values for low flows in the daily step, in order to assess and valorise the current river runoff against the defined degree of severity of the hydrological drought. An example may be found in the assessments and forecasts conducted by the US hydrological service (USGS WaterWatch), where on the basis of multi-annual runoff distributions for the single-name days of the hydrological year, critical percentiles of successive degrees of hydrological drought intensity are determined and low-flow is adopted as an indicator of its progression (Evenson et al. 2012). It should be noticed that only current discharges are subject to assessment and forecast, whereas streamflow shortages and derivative characteristics are not taken into account.

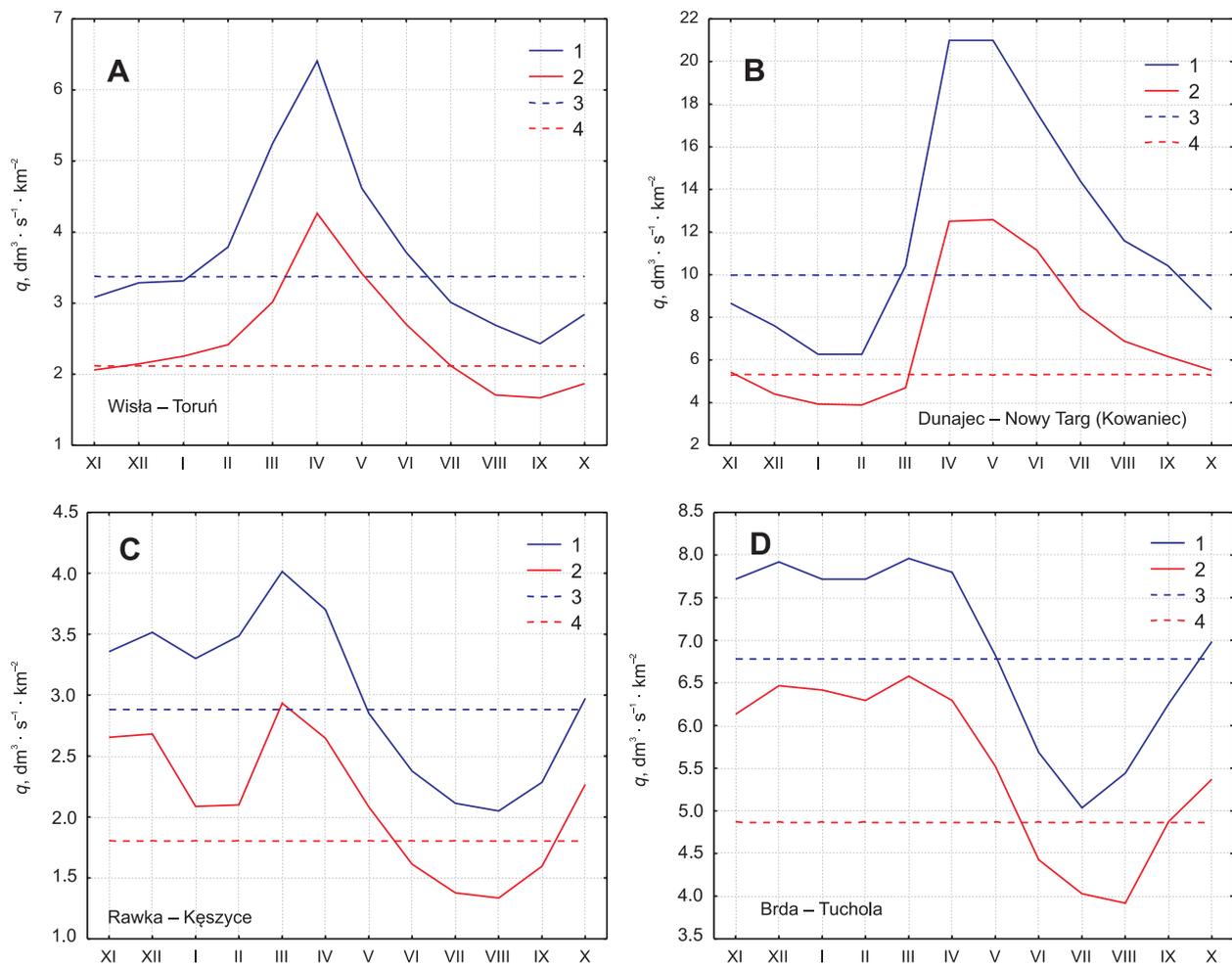
The relative deficit ( $DW_n$ ) was calculated on the basis of drought streamflow deficits, thanks to which it was possible to compare the results obtained for catchments of varying areas (Tomaszewski 2012):

$$DW_n = \frac{V_n}{V_{\max}} \cdot 100\% \quad (1)$$

where:

- $DW_n$  – relative drought streamflow deficit [%],
- $V_n$  – volume of drought streamflow deficit [ $\text{m}^3$ ],
- $V_{\max}$  – volume of the maximum possible drought streamflow deficit in the given period, that is, the low-flow for which the ordinate of discharge equals 0 [ $\text{m}^3$ ].

The above characteristic not only serves to valorise the intensity of the streamflow deficit, but it also indicates the degree of depletion of the catchment resources, which remain in a hydraulic connection with the low flow; if the ratio equals 100%, then the flow should no longer occur in the channel. This character-



**Fig. 1.** Course of constant and changeable threshold flows for total and deep low-flows in selected gauging cross-sections (1951–2016)

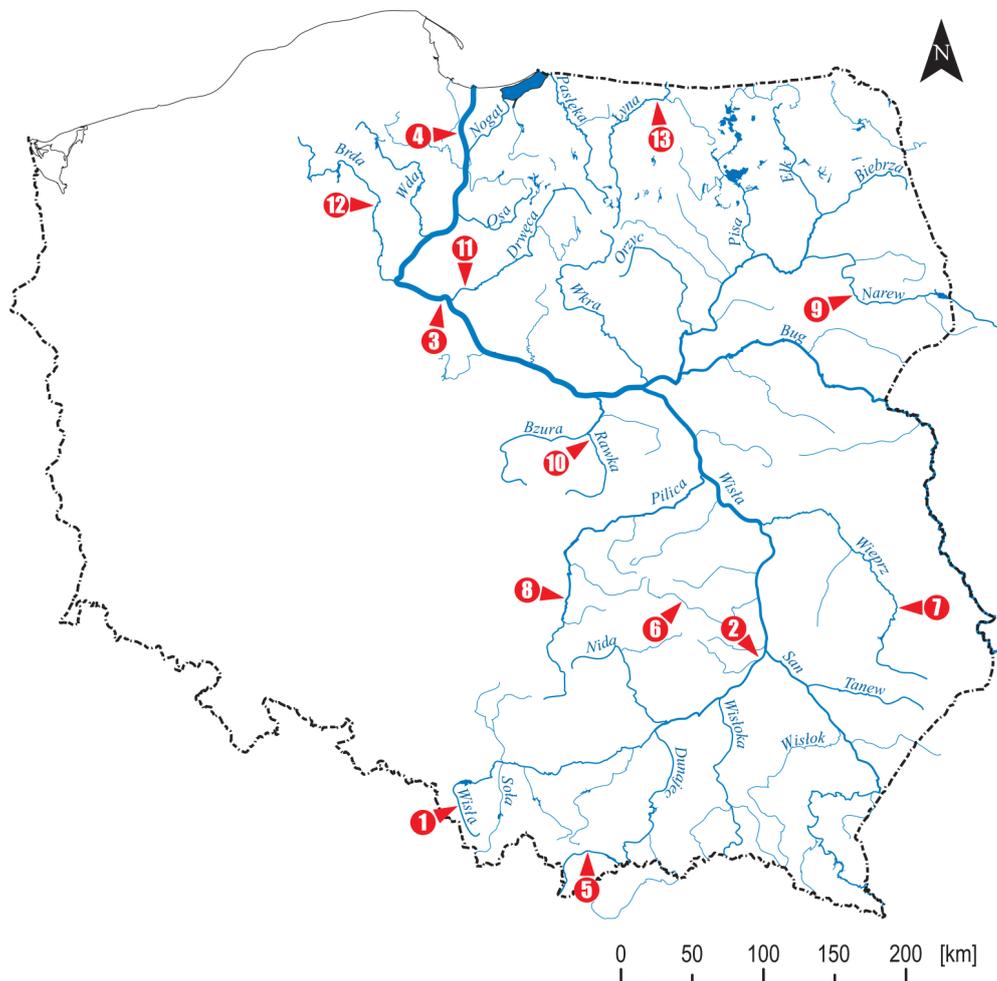
Changeable truncation flows: 1 –  $q_{70\%}$ , 2 –  $q_{95\%}$ ; constant flows: 3 –  $q_{70\%}$ , 4 –  $q_{95\%}$

istic ensures comparability of results in catchments of various sizes and is useful in the analysis of low flows occurring along transit rivers, as it is determined solely on the basis of observations coming from a given measurement cross-section.

## RESEARCH MATERIAL

Thirteen catchments located in the Vistula river basin were selected for the analysis (see: Fig. 2, Table 1). A series of daily discharges from the period 1951–2016, made available by IMGW-PIB (Polish Institute of Meteorology and Water Management-National Re-

search Institute), was obtained for each hydrometric cross-section closing the studied catchments. The adopted multi-year period guarantees the occurrence of seasons with various moisture conditions and various structures of the water balance, and thus also the appearance of hydrological droughts of various severity, extent and duration. As a result, the analysis included periods of deep and long lasting low-flows in the 1950s and 1990s, moderate shortage periods at the beginning of the 21st century, or shallow and short low-flows in the 1970s, which enabled the assessment of the almost full spectrum of the conditions that determining low flows.



**Fig. 2.** Location of the water gauges enclosing the studied catchments

1–13 – Numbering of catchments as in table 1

When choosing the catchments for the study, the author has endeavoured to obtain the selection to represent various climatic and physiographic conditions, above all, for the rivers to reflect different types of regime, especially in terms of low flows forming. Among the analysed gauges, there were 4 cross-sections located on the Vistula River, thanks to which, in the conducted analysis it was possible to take into account the specificity of drought streamflow forming along the course of the transit river (Tomaszewski 2017a). In the monthly course of threshold flows in these cross-sections, their clear increase was observed in the spring months, and a reduction in the summer-autumn period (see: Fig. 1A). It is also worth noting that in the spring

and summer months, the threshold of deep low flows is higher than the constant threshold of total low-flow. This means that it is possible to significantly underestimate the spring drought streamflow deficits from the point of view of the hydrological system dynamics. A similar course was visible in the lowland catchment of Narew river up to Suraz, however, the period of increased threshold flows is shorter in that case, which results from the specificity of low-flows occurring there, determined by climate features and a large share of wetland areas (Kaznowska 2006). An interesting seasonal distribution of threshold flows is characteristic for the mountain catchment of Dunajec river up to Nowy Targ (see: Fig. 1B). It shows a very clear re-

**Table 1.** Selected characteristics of low-flows in the catchments under investigation (1951–2016)

No.	Catchment	A	$q_{70\%}$	$q_{95\%}$	$VnR_{st}$	$VnR_{zm}$	$DWnR_{st}$	$DWnR_{zm}$	$LnR_{st}$	$LnR_{zm}$	$WGR_{st}$	$WGR_{zm}$	$\Delta N$
		km <sup>2</sup>	dm <sup>3</sup> s <sup>-1</sup> km <sup>-2</sup>		thousand m <sup>3</sup>		%		day		%	year	
1	Wisła – Skoczów	296.7	6.40	2.33	6439	6507	10.75	9.93	99.5	97.5	5.19	4.77	0
2	Wisła – Sandomierz	31846.5	4.93	3.17	303636	293961	6.13	5.53	100.9	99.6	2.66	3.49	-1
3	Wisła – Toruń	181033.4	3.38	2.12	1160103	1140839	6.01	5.48	101.4	99.6	3.00	3.53	0
4	Wisła – Tezew	194376.0	3.48	2.21	1245193	1253972	5.84	5.44	101.2	99.6	2.89	3.18	+1
5	Dunajec – Nowy Targ (Kowaniec)	681.1	9.98	5.29	17899	16658	8.35	6.61	102.5	100.2	3.15	3.57	-1
6	Kamienna – Wąchock	472.0	2.86	1.61	2915	2911	6.85	6.29	97.1	96.5	2.39	2.91	+1
7	Wieprz – Krasnystaw	3001.0	2.79	1.87	14762	15969	5.60	5.79	106.8	108.6	3.15	2.85	-1
8	Pilica – Przedbórz	2535.9	3.71	2.15	19191	17541	6.47	5.74	99.8	98.7	2.49	3.21	0
9	Narew – Suraz	3376.5	2.03	1.05	18460	20618	8.56	8.19	103.3	103.4	2.88	3.15	+1
10	Rawka – Kęszyce	1190.6	2.88	1.81	6310	5289	5.83	4.77	99.0	99.9	4.05	4.58	-1
11	Drwęca – Elgiszewo	4959.4	3.99	2.56	30609	29214	4.90	4.30	92.2	91.2	1.51	1.56	+2
12	Brda – Tuchola	2462.2	6.78	4.87	22132	15668	4.20	2.93	98.6	95.5	3.94	4.49	+2
13	Łyna – Sępól	3647.2	4.19	2.65	27227	28005	5.64	5.30	97.9	97.0	2.44	2.92	0

A – area of the catchment;  $q_{70\%,95\%}$  – low-flow threshold (percentile of the flow duration curve);  $VnR$  – average annual volume of drought streamflow deficit;  $DWnR$  – average annual relative drought streamflow deficit;  $LnR$  – average annual number of days with low-flow;  $WGR$  – average annual coefficient of drought streamflow deficit of severe phase;  $\Delta N$  – increment of the number of years with low flows, having applied the criterion of variable threshold flow; *st* – characteristics assessed for a constant threshold flow; *zm* – characteristics assessed for a variable threshold flow.

duction in characteristic flows in winter season, and their rapid growth in the spring. This is conditioned by a very large share – in fact, the largest in Poland – of winter low-flows, genetically related to snow retention and to freezing of riverbeds during the winter, followed by rapid snowmelt alimentation during the spring thaw (Tomaszewski 2017b).

Another group consisted of upland and lowland catchments, in which the threshold flows in the cool half-year were substantially lower than in the warm half-year, with the culmination in the spring months (see: Fig. 1C). In lowland catchments (Rawka, Drwęca, Łyna rivers), the basic factor determining such functioning of the system lies in summer rainfall shortages and evapotranspiration with a significant

share of warm and snowless winters (Jokieli 2004; Tomaszewski 2007). In the upland catchments (Kamienna, Wieprz, Pilica rivers), the seasonal course of threshold flows is modified by the structure, capacity and regime of groundwater reservoirs, having a significant impact on the channel alimentation in low-flow periods (Kasprzyk 2009; Tomaszewski 2012; Raczyński 2018). An example of a catchment area in which flow-through lakes play an important role is Brda river, up to Tuchola (see: Fig. 1D). The high level of flow smoothing means that during the entire cool half-year, low flows are maintained at a constant and high level, and their decreases in the summer reach their minima, falling in the months of July and August.

### MULTI-YEAR VARIABILITY

A comparative analysis of drought streamflow deficits obtained by applying the constant and the variable threshold criterion revealed multi-directional changes in the studied characteristics. In order to maintain the comparability of the streamflow deficit results obtained in absolute terms (m<sup>3</sup>), the relative deviation of the drought streamflow deficit was calculated:

$$\Delta W VnR = \frac{VnR(2m) - VnR(st)}{VnR(st)} \cdot 100\% \quad (2)$$

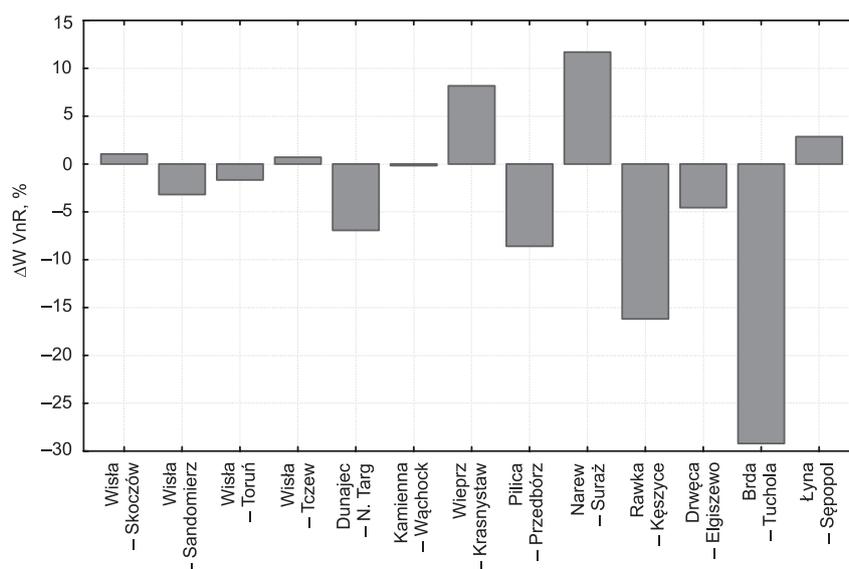
where:

- $\Delta W VnR$  – relative deviation of the drought streamflow deficit [%],
- $VnR(2m)$  – annual volume of the drought streamflow deficit calculated for the variable criterion [m<sup>3</sup>],
- $VnR(st)$  – annual volume of the drought streamflow deficit calculated for the constant criterion [m<sup>3</sup>],

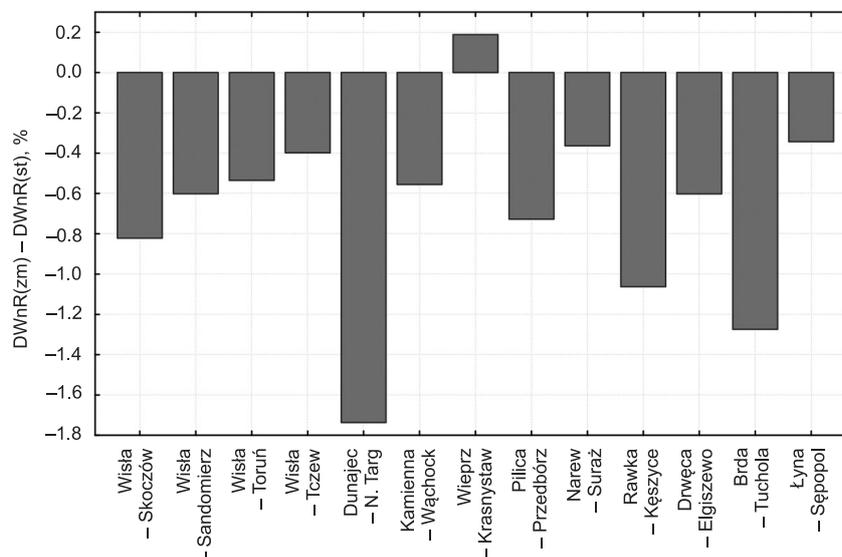
The results of relative deviations of the drought streamflow deficit indicated that the annual shortages on the upper and lower Vistula river increased slightly,

while in the middle course of that river, they decreased slightly (see: Fig. 3). However, significant differences, up to 30%, occurred in the lowland catchments of Brda and Rawka rivers. The first instance is probably related to the impact of lakes on low flows, thanks to which the smoothed, seasonal flow distribution reaches a course compatible with the seasonal distribution of threshold flows, which results in a significant reduction of summer low-flows, and simultaneously in winter flow surplus, as compared to the calculation using the constant criterion (compare: Fig. 1D). It is difficult to interpret, with no ambiguity, the results of positive deviations (in the Wieprz and Narew river catchments), because these catchments are typified by different retention level and different dynamics of the hydrologically active zone, and their only common feature is the influence of climate with more continental features than in other catchments. Most probably, it is that climate that determines the distribution of rainfall, and hence rainfall shortages, which determines a specific regime of low flows.

The results of differences calculated for average annual relative drought streamflow deficits are slightly different (see: Fig. 4). The application of the variable criterion indicates a lower degree of drainage of low-flow resources in almost all surveyed water gauge sections. The only exception is the Wieprz river catch-



**Fig. 3.** Distribution of relative drought streamflow deficit deviation calculated using the changeable and the constant criterion (1951–2016)



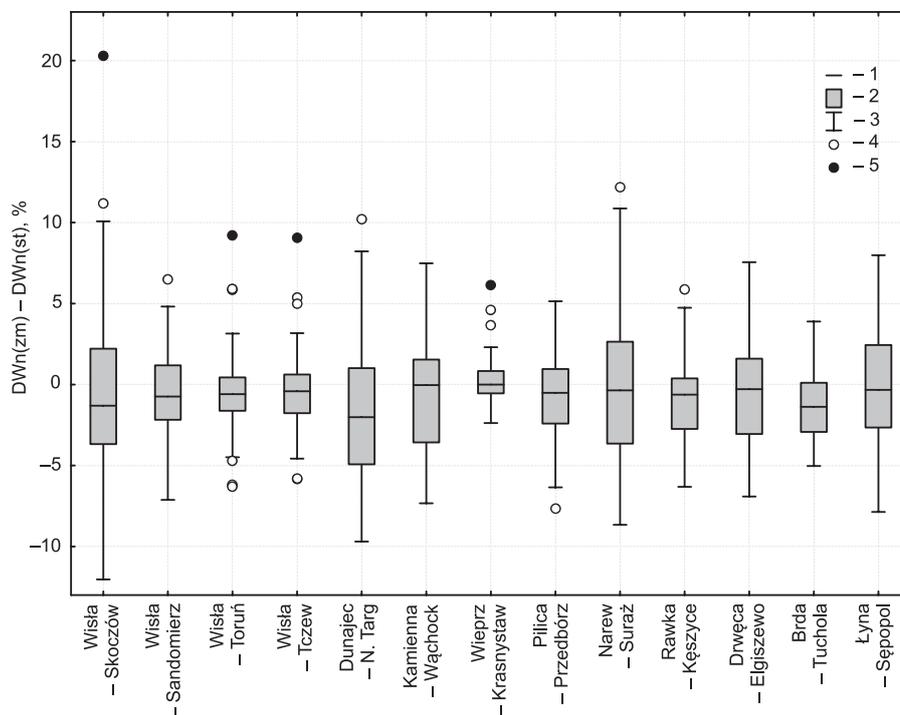
**Fig. 4.** Differences in the average annual relative drought streamflow deficit, calculated using the changeable  $DWnR(zm)$  and the constant  $DWnR(st)$  criterion (1951–2016)

ment mentioned above, characterized by a very high levelling of low flows, and a very low recession rate of groundwater resources in the dry weather phase (Jokiel 1994; Raczyński 2018). It should be noticed that the distributions of the reported differences in particular years assumed both negative and positive values in a wide range of variability (see: Fig. 5). In most cases, the boundary between positive and negative deviations fell between the median and the third quartile, which indicates slightly more than half of the years with negative deviations. In the mountainous catchments, as well as in the catchments of the Narew, Drwęca and Łyna rivers, in particular years, there was a large differentiation of deviations, which is a typical feature of the low-flow regime, while in the lower reaches of the Vistula and the Wieprz river catchment, differences of about 5% are rare.

The average annual number of days with low flow in most cases has been shortened, reaching the maximum difference of about 3 days (see: Fig. 6). Significant negative deviations covered the entire Vistula river as well as the Dunajec and Brda catchments. A reverse reaction to the application of variable threshold flow was observed in the Wieprz and Rawka catchment, whereas in the former, the average duration of low flows was extended by almost 2 days.

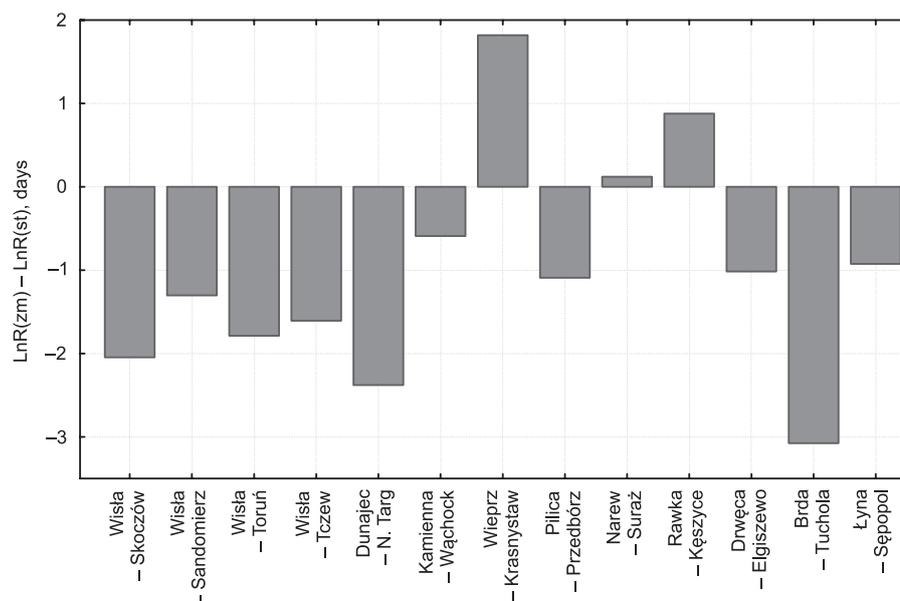
When applying the variable criterion, the streamflow deficits arising during deep low-water shortages becomes very significant (see: Fig. 7). On the majority of water gauges, the value of the  $WGnR$  parameter read higher by approx. 0.5%. However, if it will be taken into account that the typical  $WGnR$  estimated using the constant criterion was about 3% (see: Table 1), then after applying the variable threshold flow, its relative increase by over 15% was noted. Negative values were only recorded on the Vistula in the Skoczów cross-section, where  $WGnR$  estimated at a fixed and variable criterion was almost twice as high as the others, and in Krasnystaw.

It should be noticed that in the long-term perspective, after the application of variable threshold flow, the number of years in which low-flows were recorded may also change (see: Table 1). Particularly large differences were observed in the catchments of northern Poland (of the Drwęca, and Brda rivers), in which the series of low-flows have been lengthened by two. In the other cases, a similar number of differences was noted, by +/-1 year, or their absence was recorded. It indicates that the observed changes depend primarily on the individual features of the given catchment, mainly related to the specificity of the flow regime.

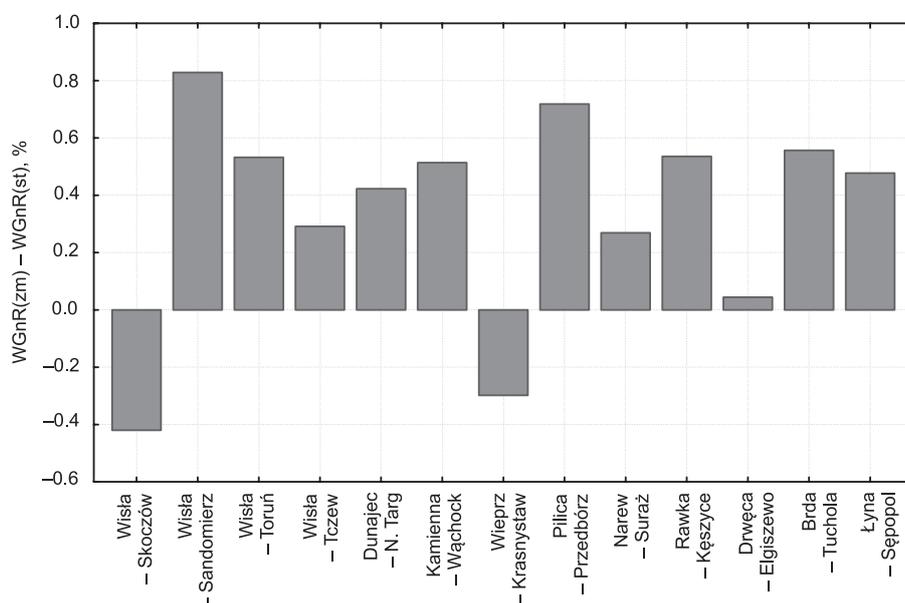


**Fig. 5.** Differences in the annual relative drought streamflow deficit, calculated using the changeable  $DWn(zm)$  and the constant  $DWn(st)$  criterion (1951–2016)

1 – median; 2 – range between the first and the third quartile; 3 – range limited by 1 quartile deviation; 4 – outliers under 1.5 quartile deviation; 5 – extremes over 1.5 quartile deviation



**Fig. 6.** Differences in the average annual number of days with low flow, calculated using the changeable  $LnR(zm)$  and the constant  $LnR(st)$  criterion, in the Vistula River gauging sections (1951–2016)



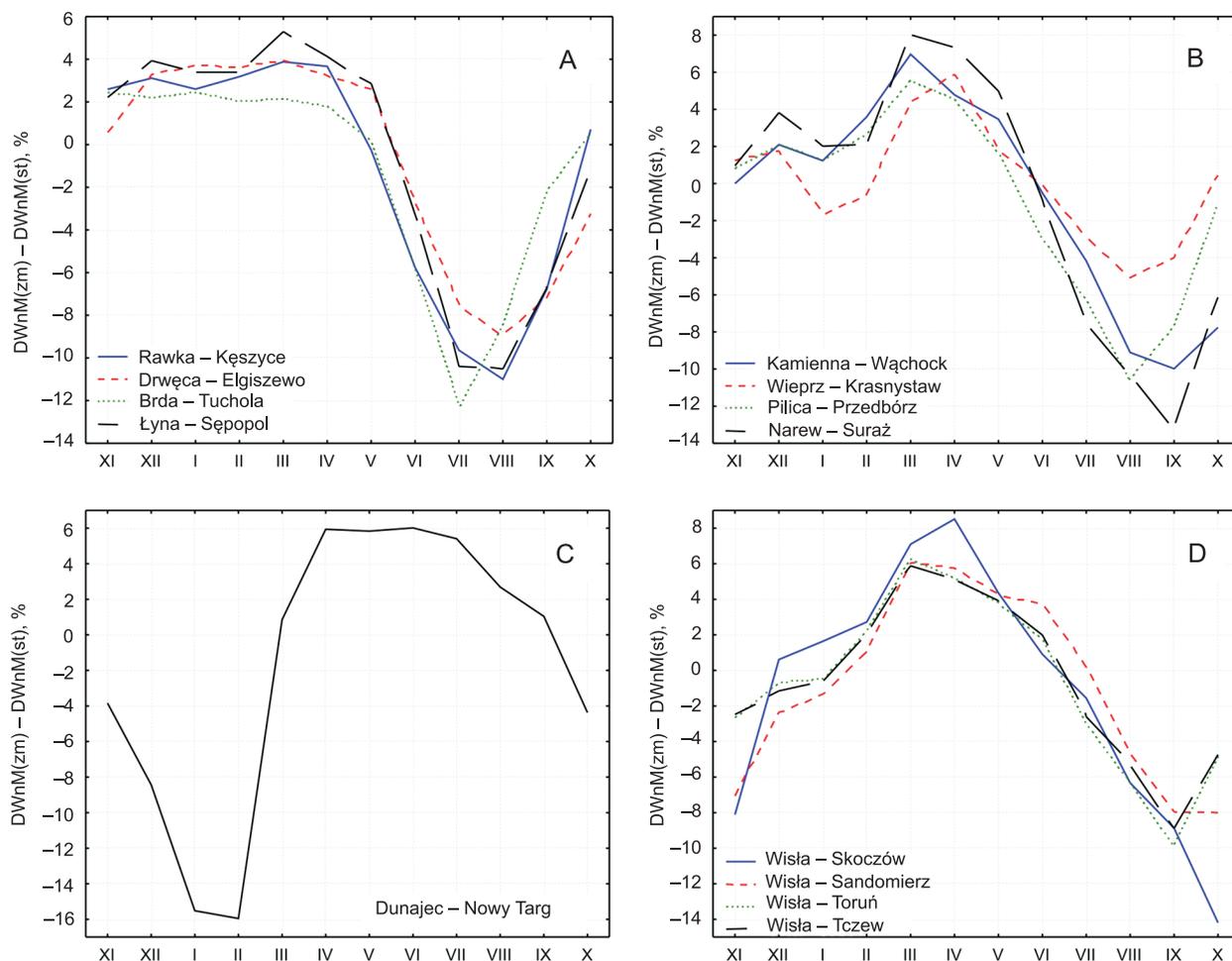
**Fig. 7.** Differences in the average annual coefficient of drought streamflow deficit of severe phase, calculated using the changeable  $WGnR(zm)$  and the constant  $WGnR(st)$  criterion, in the Vistula River (1951–2016)

## SEASONAL VARIABILITY

Differences in the seasonal distribution of drought streamflow deficits result mainly from the relationship between the monthly course of the variable and the fixed threshold flows. Furthermore, they depend on the low flows duration as well as the local factors – both natural and artificial, determining the distribution of flow. In the lowland catchments (the Rawka, Drwęca, Brda, and Łyna rivers), positive differences were observed in the cool half-year, and negative differences in the warm half-year (see: Fig. 8A). It is worth noting, however, that deviations of the deficits in the cool half-year are relatively small (about 2–4%) and close to each other in all months, which indicates similar, homogeneous conditions shaping the low flows. In the warm half-year, a clear, gradual decrease in deviations was observed until the summer minimum of –12% was reached. Therefore, in these basins, summer drought streamflow deficits resulting from the shortage of precipitation and evapotranspiration are seriously overestimated when the criterion of constant flow threshold is applied. In the upland catchments and in the Narew river catchment (see: Fig. 8B), the main changes in relation to the previous distribution were visible in the

cool half-year, and consisted of a slight increase in the spring maximum (+8%), while maintaining the division into positive differences in the cool half-year, and negative differences in the warm half-year. In the course of seasonal differences, there is also a greater variation visible between different catchments, which seems to result from the diversity of hydrogeological conditions that modify the course of relative drought streamflow deficits when applying the variable flow threshold.

The individual course of seasonal differences in drought streamflow deficits was recorded in the Dunajec catchment (see: Fig. 8C). Very large deviations in the winter period (–16%) and low variations in the warm half-year deviations (+6%) are inversely proportionate to the course of differences observed in lowland catchments. A large share of winter low-flows, typical of that river’s regime, causes the use of constant threshold flow to generate significant overestimation of drought streamflow deficits in that season. Different results were obtained for the transit river (see: Fig. 8D). In the Vistula’s water gauges cross-sections, regardless of the size of the catchment and the number of tributaries adopted upstream, the seasonal distribution of the differences in drought streamflow deficits was very similar in all cases. Positive devia-

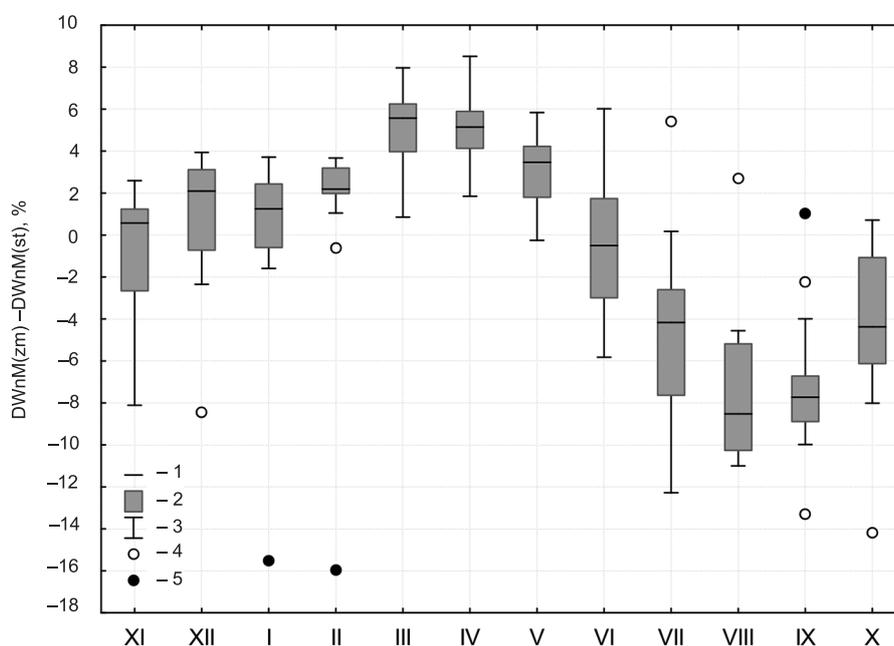


**Fig. 8.** The course of differences in monthly values of relative drought streamflow deficit, calculated using the changeable  $DWnM(zm)$  and the constant  $DWnM(st)$  criterion (1951–2016)

tions concerned the spring months and the month of June. The amplitude of the observed differences is also relatively small: between + 8% and –10%. Therefore, it can be concluded that the dynamic features of the low flow regime, related to their seasonal distribution, formed in the upper reaches of this river, are transmitted to the estuary, despite the significant tributaries with different characteristics of the water regime.

After compiling the monthly relative deviations of the drought streamflow deficits in all analysed catchments, it can be observed that the average differences show a gradual, almost sinusoidal change from month to month (see: Fig. 9). After applying the variable threshold flow, the positive differences in  $DWnM$  are

characteristic for the period from November to May. In turn, negative differences occur in season from June to October. In the presented distribution, there were only 2 extremes, falling to the months of March and August, whereas the difference between the  $DWnM$  medians calculated for these months was over 14%. It is worth noting that the least diverse variations occur in the winter-spring period. During summer and autumn, due to large differences in hydro-meteorological conditions between particular years and the variable evapotranspiration, the differences in the results obtained using the two criteria are very diverse. The exceptions are outliers, generated mainly by the Dunajec catchment in winter. Therefore, using seasonally variable criteria for



**Fig. 9.** Distribution of differences in monthly values of relative drought streamflow deficit, using the changeable  $DWnM(zm)$  and the constant  $DWnM(st)$  criterion (1951–2016)

1-5 – Numbering as in figure 5

the summer-autumn period can significantly enrich the knowledge about the formation of low flows.

## CONCLUSIONS

The conducted research indicates that the application of constant and variable threshold flow produces significantly different results in the volume of drought streamflow deficit, and in the characteristics of low flows. Differences in average values calculated over a multi-year period, are relatively small, however, their variability from year to year reflects high dynamics. The assessment of the distribution of seasonal differences in drought streamflow deficits revealed clear geographical and hydrological conditioning. Different types of distributions were observed for lowland, upland and mountain catchments. Along the entire course of the Vistula river, the distributions of monthly deviations exhibited a high similarity, which testifies to the transit transfer of dynamic features of the low-flow regime related to their seasonal distribution from the sources to the estuary. Multidirectional deviations

of drought streamflow deficits in different seasons, and in different types of catchments, indicate that the use of variable low-flow threshold can provide a lot of new information about the formation of low flows, especially in relation to the dynamic hydrological system and its natural conditions.

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## OCENA NIEDOBORÓW ODPLYWU NIŻÓWKOWEGO PRZY STAŁYCH I ZMIENNYCH PRZEPŁYWACH GRANICZNYCH NA PRZYKŁADZIE WYBRANYCH ZLEWNI DORZECZA WISŁY

### ABSTRAKT

W opracowaniu dokonano oceny niedoborów odpływu niżówkowego i charakterystyk przepływów niżówkowych przy stałym i zmiennym (miesięcznie) przepływie granicznym niżówki. Niżówki całkowite identyfikowano w oparciu o 70. percentyl z krzywej czasów trwania przepływu wraz z wyższymi ( $Q_{70\%}$ ). Za przepływ graniczny niżówki głębokiej przyjęto  $Q_{95\%}$ . Do badań wytypowano 13 zlewni leżących w dorzeczu Wisły, charakteryzujących się różną wielkością, reżimem rzeczonym i warunkami fizycznogeograficznymi. Danymi wejściowymi były serie dobowych przepływów z okresu 1951–2016, udostępnione przez IMGW-PIB. Analizie poddano objętość niedoboru odpływu niżówkowego wyrażonego wartościami względnymi i bezwzględnymi, czas trwania przepływów niżówkowych oraz udział niedoborów odpływu pojawiających się podczas niżówek głębokich. Badania prowadzono w układzie rocznym i miesięcznym. Porównanie uzyskanych wyników doprowadziło do określenia podstawowych czynników wpływających na formowanie niedoborów odpływu niżówkowego oraz wskazania ograniczeń przy stosowaniu stałych i zmiennych kryteriów identyfikacji niżówki rzecznej.

**Słowa kluczowe:** reżim przepływów niżówkowych, przepływ graniczny niżówki, susza hydrologiczna, dorzecze Wisły