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SEASONALITY LEVEL OF HYDROLOGICAL DROUGHT IN RIVERS AND ITS VARIABILITY

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Abstract

The aim of this study is an estimation of seasonality index and period of concentration of hydrological drought in lowland catchments. It was based on Markham's indices, originally used to precipitation analysis, and adopted to drought streamflow deficit estimation by the author. A set of 29 water-gauges, situated in the Warta, Pilica and Bzura River basins (central Poland) was selected to investigation. Basic calculations were made on daily discharge series from the period 1951-2002. In the first step, low flow episodes were identified on the base of the threshold-level method with $Q_{70\%}$ as a truncation level, derived from flow duration curve. It allowed to estimate streamflow deficit volumes which were recalculated in monthly-step series. On that base the seasonality index as well as period of seasonal concentration of hydrological drought for particular years as well as whole multiyear were calculated. Analyses involved spatial and temporal aspects of investigated characteristics. Question of variability was investigated on the base of variation coefficient as well as the index of mean change year by year. Special attention was attracted to factors which determine studied phenomenon, multiannual variability and statistically significant trends appearance.

Keywords: low flows, hydrological drought, streamflow deficit, river regime.

1 INTRODUCTION

Hydrological droughts and low flows are very important components of a river regime. These phenomena have a great impact on the areas with restricted water resources and adverse structure of water balance. Water shortage is determined by many factors whose activity is considerable stretched in time. Therefore, in the context of observed and predicted climatic changes, many lowland areas in Europe are partly affected or seriously put at risk of negative consequences of water deficit for public services, industry, agriculture and forestry as well as water ecosystems degradation. Results of hydrological drought and low flow analyses in seasonal and multiannual scale might improve strategies of hydrological extremes prevention as well as help in efficient water resources management during restricted alimentation periods.

The hydrological drought is usually defined as a period during weather when low flows appear in a river channel (Smakhtin, 2001). The origin of this is closely connected with restricted alimentation, determined by lack of precipitation and high evapotranspiration in summer or cutting off drainage channels by frozen ground (in winter). The length of the restricted alimentation period as well as the relationship between the recession and recharge rate of groundwater resources have a great impact on the evolution of a drought event where its duration and water shortage volume are the most important factors for the estimation of the level of drought severity.

One of the most common methods for the delimitation of a hydrological drought event is to determine the threshold level. A period during which discharge attains values below an established limit is defined as a streamflow deficit period (Yevjevich, 1967; Ozga-Zielińska, 1990; Hisdal et al., 2004). Its two basic parameters are low flow duration and deficit volume (Fig. 1).

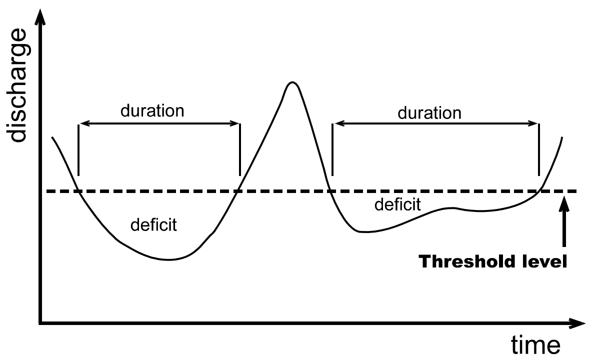

Figure 1. Basic parameters of a hydrological drought

There are two methodological approaches that allow a proper threshold to be selected: statistical and conventional – based on water management. The first approach assumes that the threshold can be derived from a flow duration curve such as the percentage of exceedance from the range of between 70% (Q_{70}) and 95% (Q_{95}) (Hisdal et al., 2004; Tomaszewski, 2011, 2012). The latter uses annual (or monthly) minimum daily discharge series for the calculation of such threshold indices as SNQ – mean value, WNQ – maximum value or ZNQ – median value, cf. Ozga-Zielińska (1990).

2 METHODS

Hydrological drought as an extreme phenomenon occurs very irregularly, because water shortage depends on determinants which change seasonally (precipitation, temperature, evapotranspiration, snow cover etc.) as well as in multiannual scale (e.g. series of dry and wet years). Almost every drought develops as a result of both group of components activity which are very difficult to separate. Therefore low flows frequency of appearance and severity is very changeable and hard to predict. Because of this, seasonal analyses based on monthly step intervals are significantly limited. A good solution of the problem may be an application of complex assessment indices of seasonal variability.

The seasonal variability of streamflow deficit was estimated on the basis of Markham (1970) indices. The level of irregularity of annual deficit volume distribution as well as its concentration time were calculated based on angular characteristics. The original version of the procedure was designed for precipitation analysis. After a few methodical transformations, two new characteristics of seasonality were defined: seasonality index (IS) and time of seasonal concentration (WPK) of hydrological drought. At the basis of the procedure is made an assumption that each of the 12 months is represented by vector whose length is determined by monthly streamflow deficit volume (r_i) and its angle depends on midpoint position of the given month in relation to the beginning of the year (α_i):

$$\alpha_i = \frac{360 \cdot S}{365} \qquad (1)$$

where: *S* – number of days between the beginning of a hydrological year and the midpoint position of the given month.

For group of 12 estimated vectors there is identified the resultant vector R with modulus |R| and direction ω (Fig. 2). Dividing the length of the resultant vector |R| by the sum of the 12 vectors $|r_i|$ seasonality index (IS) is estimated:

$$IS = \frac{|R|}{\sum_{i=1}^{12} |r_i|} \cdot 100\% \qquad (2)$$

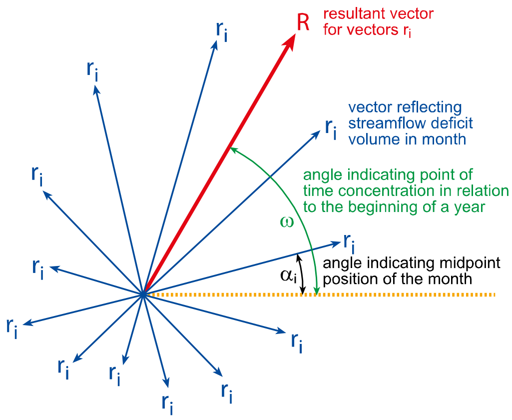

Figure 2. Idea of Markham procedure

IS value varies between 0% which means total regularity (the same streamflow deficit volume each month) and 100% which is determined by total concentration where drought streamflow deficit occurs in one month only. The second characteristic – the time concentration index (WPK) – is represented by the angle of the resultant vector (ω) and indicates the day (or the month) of the year of streamflow deficit concentration:

$$WPK = arctg\left(\frac{\sum_{i=1}^{12}|r_i|\cos\alpha_i}{\sum_{i=1}^{12}|r_i|\sin\alpha_i}\right)\cdot\frac{365}{360} \tag{3}$$

3 STUDY AREA AND DATA

The study area consisted of three river basins – the Warta, Pilica and Bzura – located in the central part of Poland. A set of 29 water-gauges situated in these basins were selected for analysis (Fig. 3). All of the gauges, encompassing small and medium autochthonous catchments, reflected simple regimes of small rivers in homogeneous basins, as well as more complex regimes in larger basins of heterogeneous water courses – catchment area varies between 250 and 50,000km^2.

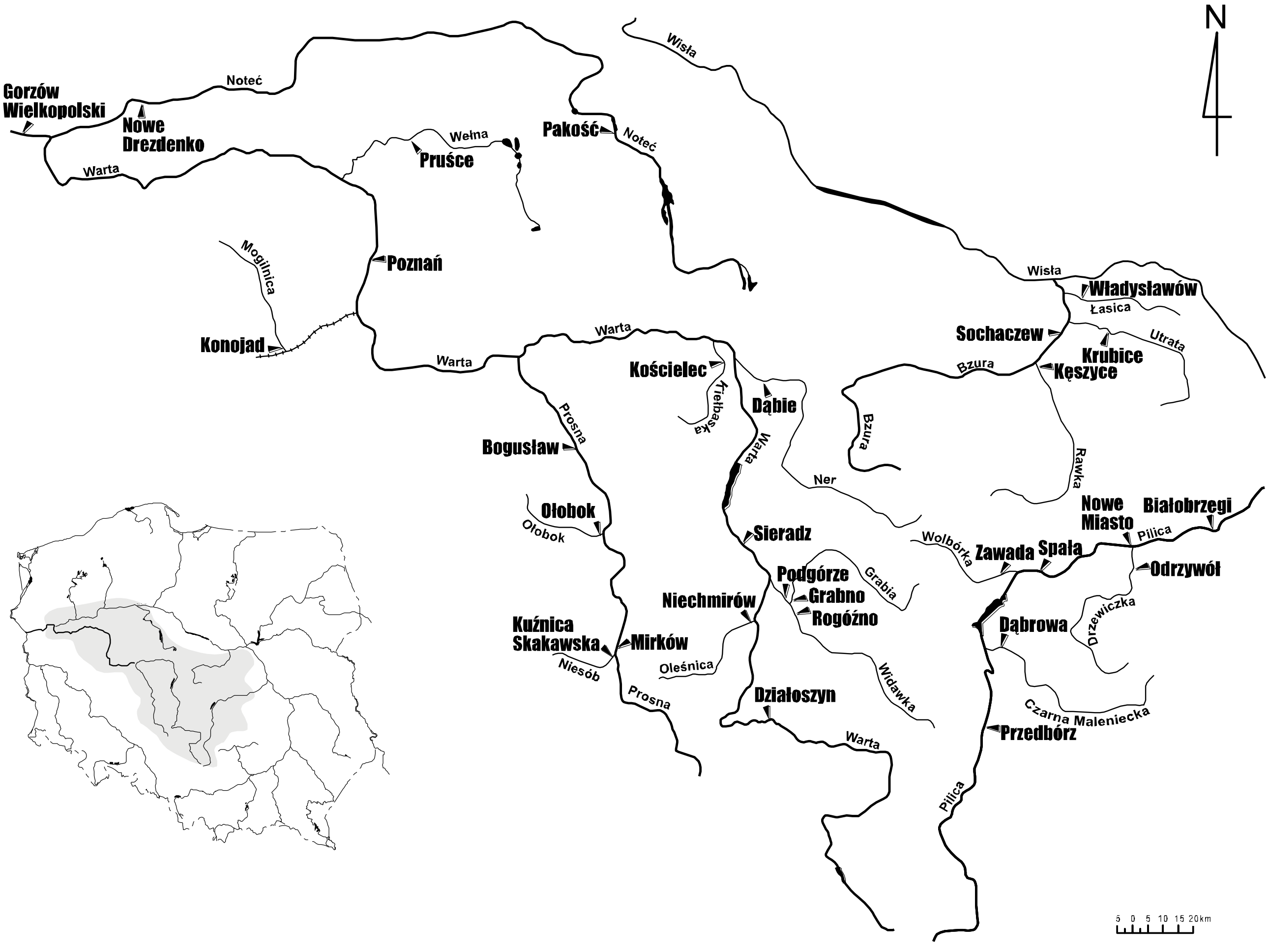

Figure 3. Location of the analysed water-gauges

Basic calculations were made on daily discharge series from the period 1951–2002, measured by the Polish Institute of Meteorology and Water Management. To estimate streamflow deficit the threshold method was applied, where, as a significant truncation level, the percentile Q_{70} from flow duration curve was accepted. For each of the identified low-flow episode, streamflow deficit volume and its duration time was estimated. Collected data was recalculated into monthly step scale. On that base seasonality index (IS) and time of seasonal concentration (WPK) of hydrological drought was estimated for particular years (Fig. 4A) as well as whole multiyear (Fig. 4B).

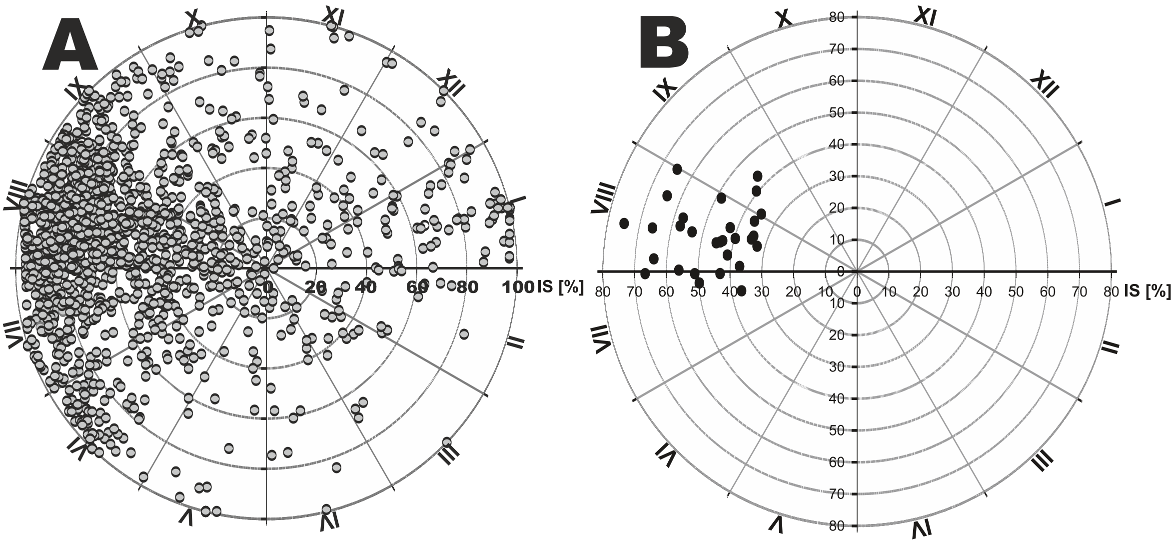

Figure 4. Location the vector heads of seasonality index and time of seasonal concentration of hydrological drought calculated for particular years (A) and for multiyear (B).

4 RESULTS AND DISSCUSSION

The average value of seasonality index in the group of investigated catchments is equal 44% (Fig. 5). Half of them vary between 40 and 57%. Extremes of analysed distribution were located on 32.4% (Pilica – Spała) and 74.8% (Łasica – Władysławów). It is worth noticing that hydrological droughts are characterized by a very high level of seasonality. The same variables on the investigated area attained very different values of IS for groundwater flow (10–20%; Tomaszewski, 2007), precipitation (20–30%; Kożuchowski & Wibig, 1988), and total runoff (20–40%; Bartnik & Tomaszewski, 2006). There is also interesting that appears a huge group of years when seasonality level achieved 100% (Fig. 4A). It indicates that in low-flow regime very important role is played by short summer low-flow episodes.

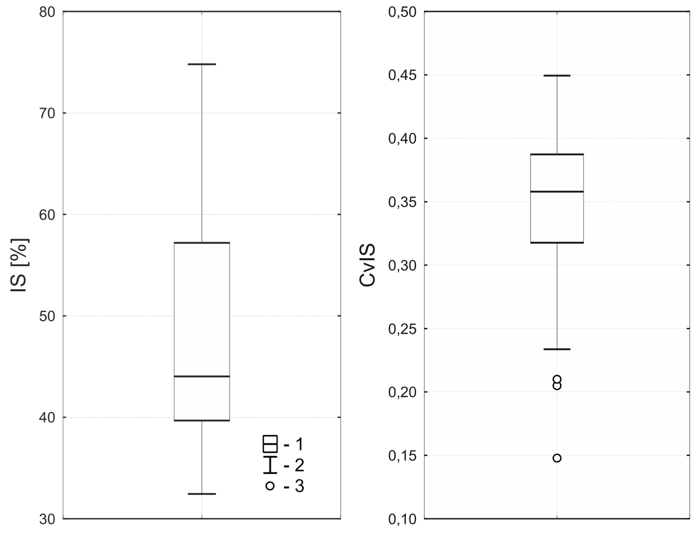

Figure 5. Distribution of seasonality index of hydrological drought (IS) and its variation coefficient (CvIS) 1 – lower quartile – median – upper quartile, 2 – range below 1,5 quartile deviation, 3 - outliers

Distribution of calculated IS values manifests a light positive skewness. The lowest seasonality index was calculated for gauging station Spała on the Pilica River (Fig. 3, 6). It is located about 15 km downstream of dam which closing the Sulejowski Reservoir. Such low level of hydrological drought seasonality is caused by reservoir strategies which reduces negative effects of water shortage during dry periods. In regional scale, lower level of hydrological drought seasonality occurred in the Pilica River basin what is determined by capacious groundwater reservoirs made of well fissured carbonated rocks. Their regime has a crucial impact on decrease of discharge recession pace during groundwater alimentation as well as slope of master recession curve. High level of hydrological drought seasonality is observed in catchments with lakes where local discharge extremes are stored and buffered by lake basin which prevents from breaking of drought episode progression downstream. High low-flow seasonality is also noticed in small river systems placed near main watershed divides where river channels dissect groundwater reservoirs very shallowly. As a result, summer hydrological droughts appear there very quickly and stay stable on severe level.

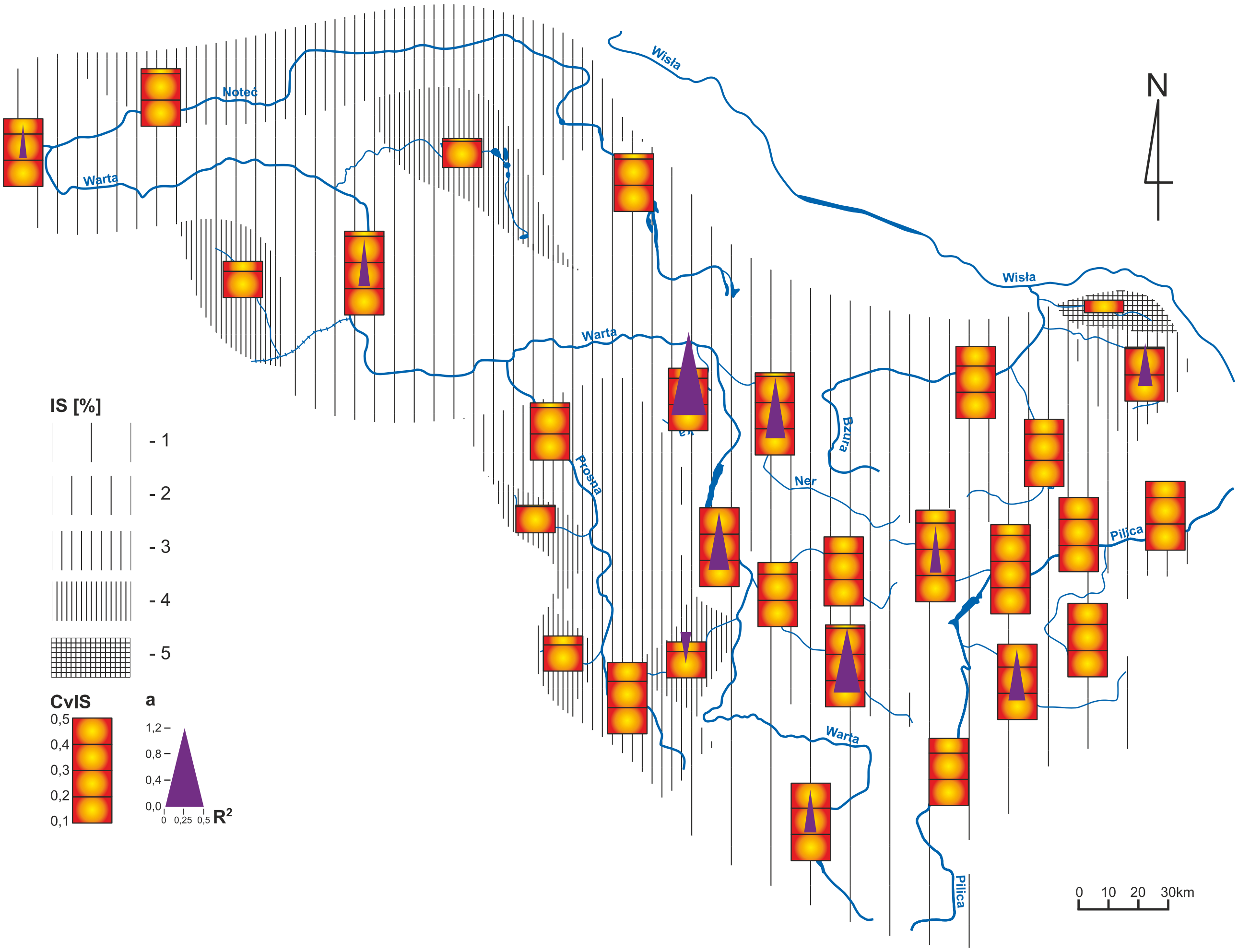

Figure 6. Seasonality index of hydrological drought and its variability (1951-2002)
Seasonality index of hydrological drought (IS) [%]: 1 – 30,1-40,0, 2 – 40,1-50,0, 3 – 50,1-60,0, 4 – 60,1-70,0, 5 – 70,1-80,0; CvIS – variation coefficient of IS, a – statistically significant slope coefficient of linear trend equations (α = 0,01), R^2 – determination coefficient of approximated linear trend.

Multiannual stability of seasonality index was analysed on the base of variation coefficient which is defined as a quotient of standard deviation and arithmetic average (CvIS). Mean multiannual variability of seasonality index is not too high because is equal 0.36 (Fig. 5). Total range of CvIS is limited by 0.15 and 0.45, however, a light negative skewness indicates that a few rivers is characterized by much more stability of IS than the others. This phenomenon involves catchments with lakes and systems placed near main watershed divides (Fig. 6). In the other investigated rivers multiannual dynamics of irregularity level of hydrological drought is very similar which is proved by very narrow range between upper and lower quartile.

In a few rivers statistically significant linear tendency of changes in seasonality index was noticed (Fig. 6, 7). The strongest trends appeared in catchments where the flow regime exists under a strong anthropopressure (the Widawka, Ner, Kiełbaska river). However, not a slope coefficient of estimated equations but determination coefficient (R^2) indicates the strength of human impact. Its values proved that systematic time component determines from 26 to 45% of total variability of hydrological drought seasonality index. In the other investigated rivers determination coefficients are crucially lower, however, it is worth noticing that along the whole Warta river gradual arise of seasonal coefficient exists which is determined by water management.

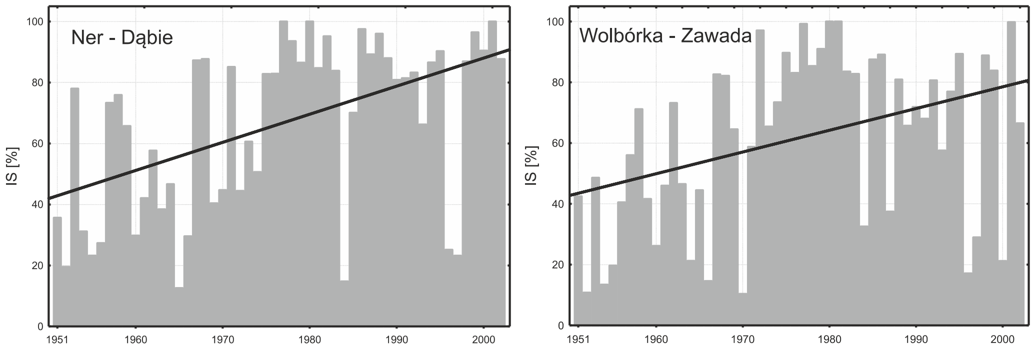

Figure 7. Examples of statistically significant trends in annual course of seasonality indices of hydrological drought

Average time of seasonal concentration of hydrological drought varies between 22nd of July and 14th of September (Fig. 4B). Relatively low changeability of WPK is probably caused by high homogeneity of conditions determining of time concentration. It indicates high importance of climatological factors which are active in scale of the whole investigated region, especially depended on hydrometeorological conditions – precipitation and evapotranspiration. Low-flow streamflow deficits occur most often on summer and are highly severe because of fully development of vegetation (Fig. 4A). On autumn severe hydrological droughts may appear as well, however, this phenomenon is rather rare and usually caused by prolonging summer droughts.

5 CONCLUSIONS

Presented studies lead to conclusion that seasonality level as well as time concentration period of hydrological drought demonstrate significant and multidirectional changes. Mean time concentration periods of drought streamflow deficit fall on summer season, mainly on August. Their distribution is determined mostly by hydrometeorological conditions (precipitation, evapotranspiration). Seasonality index of hydrological droughts reflects capacity and regime of active exchange zone reservoirs as well as may depend on water management. Moreover, multiannual variability of seasonality index is very prone to anthropogenic impact. In rivers where low flows are formed under strong anthropopressure, this characteristic demonstrates statistically significant upward linear trends which result in continuous deepening of water shortage during summer season.

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