# Chapter 12
# Dynamics, Range, and Severity of Hydrological Drought in Poland

**Edmund Tomaszewski and Malwina Kozek**

**Abstract** The chapter discusses a phenomenon of hydrological drought based on the assumption that river low flow serves as a good estimator of the drought development. The study analyzed 87 catchments of Polish rivers with a total surface exceeding 317 thousand $km^2$, and covering almost the entire area of the country. Basic data on daily series of discharges at the gauging cross-sections closing the catchments were collected in the years 1985–2014. Low flows were identified with reference to threshold level method matching 70 and 95 percentile at a flow duration curve as constant, multiannual truncation level ($Q_{70\%}$, $Q_{95\%}$). The identification and separation criteria allowed for identification and analysis of the course of mild and severe hydrological droughts in Poland. The research covered parameters describing duration, severity, range, and identification of periods with different patterns of hydrological drought development. An analysis of multiannual and seasonal variability of the phenomenon and selected genetic relationships enabled identification and evaluation of the factors determining the development of hydrological drought in Poland. Seasonal properties of the drought were additionally assessed with a two-parameter analysis of seasonality degree and concentration date involving angular measures. The study findings and conclusions are of cognitive as well as practical nature and can be applied to improve the effectiveness of water management aimed at mitigating the effects of drought.

**Keywords** Hydrological drought · Low flows · Threshold level method · Flow seasonality · Poland

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## 12.1 Introduction

Drought is one of the most unfavourable effects of weather and climate variability. It is usually defined as an exceptionally dry (rainless) period long enough so that water deficit seriously disturbs the structure of water balance within a specific area [1, 2]. Its basic feature is limited access to water resources. Drought is usually initiated by rainfall shortage (meteorological drought) (see Fig. 12.1). However, the rainfall shortage initiates this stage of drought only when it occurs in a typical period of groundwater alimentation with precipitation or when, due to various factors, groundwater retention is very low. In practical terms, this stage is identified based on relative deviations of rainfall characteristics from standard values or multiannual means [3, 4]. Apart from the amount of total precipitation, its time distribution and intensity also play important roles. Limited rainfall supply to groundwater reservoirs is usually exacerbated by evapotranspiration. In Poland, the areas with the highest risk of atmospheric drought include Central Poland Lowlands and western part of the Pomeranian Lakeland [5, 6].

Prolonged lack of precipitation combined with intense evapotranspiration result in gradual loss of soil moisture within the vadose zone. At first, infiltrating gravitational water and suspended vadose water disappear, then capillary water, and in extreme cases even adhesive water. This process is accompanied by an increase in soil capillary potential, the value of which directly depends on the time necessary to restore field capacity so that effective infiltration could begin. As the infiltration is very slow, single precipitation events during drought do not supply groundwater, because properties of the dried soil are similar to those of the impermeable layer.

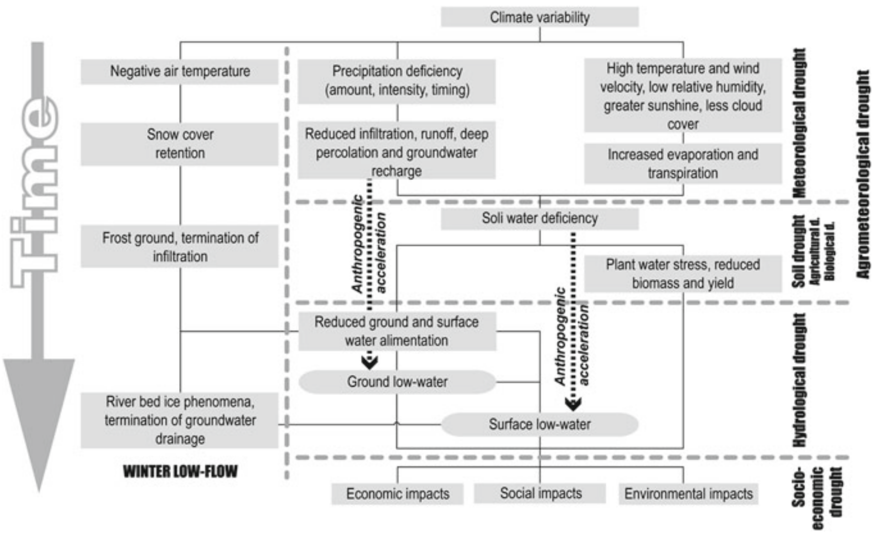


**Fig. 12.1** Diagram of drought development (after [7], modified)

This may sometimes intensify surface runoff and evaporation, i.e., the processes conducive to soil drought. If water shortage is translated into measurable losses manifested by plant degradation and restricted growth or if drought periods overlap with intense field works, agricultural drought may occur [8]. Individual plant species show different tolerance to soil water deficiency, which is why the concept of agrometeorological drought involves relationships between precipitation and plant growth conditions. An official indicator of agricultural drought in Poland is the climatic water balance (CWB). The metric is used by the Agricultural Drought Monitoring System[1] that evaluates drought severity between 1st April and 30th September in 13 six-decade periods for various plant species. In communes where CWB threshold values are exceeded, the monitoring data are the basis for compensation claims.

Further increase of water deficit results in hydrological drought [2, 9–12]. The non-supplied aquifers are continually drained by watercourses and springs. As a result, the elevation of their water table declines and low groundwater period occurs. This is accompanied by a systematic decrease in surface water resources, which are usually in a hydraulic connection with groundwater. These mechanisms facilitate the appearance of summer and autumn low flows. Recession rate of the groundwater resources of the active exchange zone in this period, and thus the rate of low flow development, depend nearly exclusively on the retention level of groundwater reservoirs [13–15].

Winter low flows of surface waters follow a different course. Limited runoff is then due to temporary water retention in the snow cover often combined with riverbed freezing during severe frosts that stops all forms of drainage (Fig. 12.1). This is not a global problem, but in the countries with a harsh climate, it may severely disturb water management [16–18]. It is worth noticing that winter drought does not consist in water shortage but its entrapment in the form of snow and ice. This means it is highly seasonal and water resources are retained "on the spot".

Severe hydrological droughts bring about serious losses to water consumers, and this is why a concept of a socio-economic drought has been coined. The effects of such a drought may be perceptible at the national scale [10]. Disturbed functioning of water-power engineering or agricultural production affects economy. Water shortage impacting municipal services management is classified as social effects of drought, while the degradation of aquatic ecosystems, especially during the blooms of toxic algae causing significant decline of water quality, is the manifestation of its environmental effects.

Human activities currently interfere with all stages and links of drought development (see Fig. 12.1), and in some cases, may accelerate its advancement [7]. Agrotechnical treatments aimed at ensuring optimal conditions of plant growth need to be initiated as soon as rainfall shortage brings about meteorological drought. Irrigation is then intensified by using local groundwater resources and providing water to plants via sprinkling machines or other forms of watering. Water collected from the saturation zone does not infiltrate back to the groundwater reservoirs but is removed during evapotranspiration. This results in simultaneous development of atmospheric

[1] https://www.susza.iung.pulawy.pl/en/.

drought and low flows of low groundwater levels, often without the soil drought stage. At the next stage, groundwater resources are exhausted, and surface water reserves need to be mobilized to mitigate the soil drought. However, by this time the drought severity is so strong that water redistribution quickly leaps from local to regional scale and results in low flow of rivers. As a result, when the hydrological drought should only naturally begin, low flows of underground and surface waters are already highly advanced.

Many regions of the world, where the effects of drought are particularly harsh or dangerous, introduced early warning systems. They improve and implement methods for short-term and seasonal forecasting of drought and develop an integrated information exchange system between networks. They include various scenarios of drought development and emergency plans at the state and regional levels. The systems also assess the risk of individual events and available insurance options [19]. Drought risk assessment in Poland involves not only the strategies of mitigating its effects but also the process of drought risk management [20].

## 12.2 Methodology and Data

River low flow, i.e. the last stage of the response to insufficient supply, is considered a good indicator of hydrological drought [21–23]. It is usually defined as a period of low flows (water levels) in a river or flows maintained during dry weather [14, 24]. Precise definition of the low flow depends on a specific research approach. One of them is a threshold level method in which an analysis of a flow hydrograph with respect to a threshold value determined based on a selected characteristic flow enables identification of the low flows. Limit values are estimated based on second degree main flows, periodic flows from the flow duration curve, analysis of annual minima distribution or conventional flows adapted to specific challenges of water management and environmental management. In this research approach, the low flow is a period with flows lower than the established threshold flow [25–27]. As a consequence, the basic parameters of the identified phenomenon include the volume of discharge deficit in the period when it is lower than the threshold flow and the duration of the low flow event (Fig. 12.2a).

The calculated deficits of drought streamflow were transformed into a relative deficit (RVn), which made it possible to compare results from catchments of variable surface area [7]. The presented characteristic is calculated as per the following formula:

$$RVn = \frac{Vn}{Vmax} \cdot 100\% \qquad (12.1)$$

where:

RVn relative drought streamflow deficit (%),

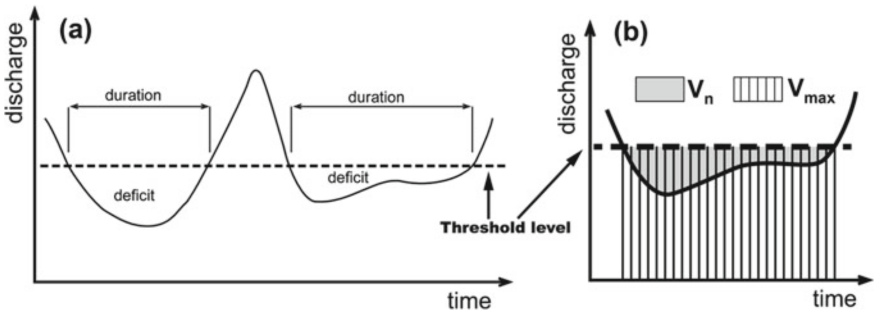


**Fig. 12.2** Basic parameters of low flow episodes (**a**) and graphic analysis of the calculation of relative low flow discharge deficit (**b**) (after [7], modified). $V_n$ – volume of drought streamflow deficit ($m^3$), $V_{max}$ – maximum volume of possible drought streamflow deficit for a given period, i.e. when the river discharge value equals 0 ($m^3$)

Vn volume of drought streamflow deficit ($m^3$),
Vmax volume of maximum possible drought streamflow deficit for a given period, i.e., when the river flow value equals 0 ($m^3$).

This measure not only evaluates the intensity of the deficit but also indicates the degree of the catchment resources drainage that shows a hydraulic connection with the low flow. When the metric equals 100%, no flow in the riverbed should occur (Fig. 12.2b), so it can serve as an estimator of the hydrological drought severity. Moreover, it ensures full comparability of results in catchments of various sizes and is useful in the analysis of low flows occurring along transit rivers, as it is based on observations from a specific gauging section only.

The study covered 87 water gauges from Poland (see Fig. 12.3). Total catchment area closed with these gauging sections exceeds 317,000 $km^2$. Their location reflects a full spectrum of possible river regimes occurring in Poland, as well as the variety of physico-geographical conditions that affect the shaping process of low flows and their deficits. The analysis covered the observation period 1985–2014. It is long enough to meet the reliability threshold for hydrological analyses advocated in the literature to be at least 30 years, and it reflects the current status of the investigated phenomenon.

The calculations were based on the series of daily discharges collected and shared by the Polish Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in Warsaw. The flow corresponding to 70th ($Q_{70\%}$) percentile at the flow duration curve was assumed as a truncation level for low flows. The study assessed the number of days with the low flow for individual months and years of the analyzed period, and the streamflow deficit volume in absolute values that was converted into the relative deficit (RVn). It also identified severe low flows that occur when the seasonally renewable resources in the hydrologically active zone are depleted, and supply is provided exclusively by the aquifers characterized by a multiannual rhythm. The truncation level for severe low flows was set at 95 percentile [7].

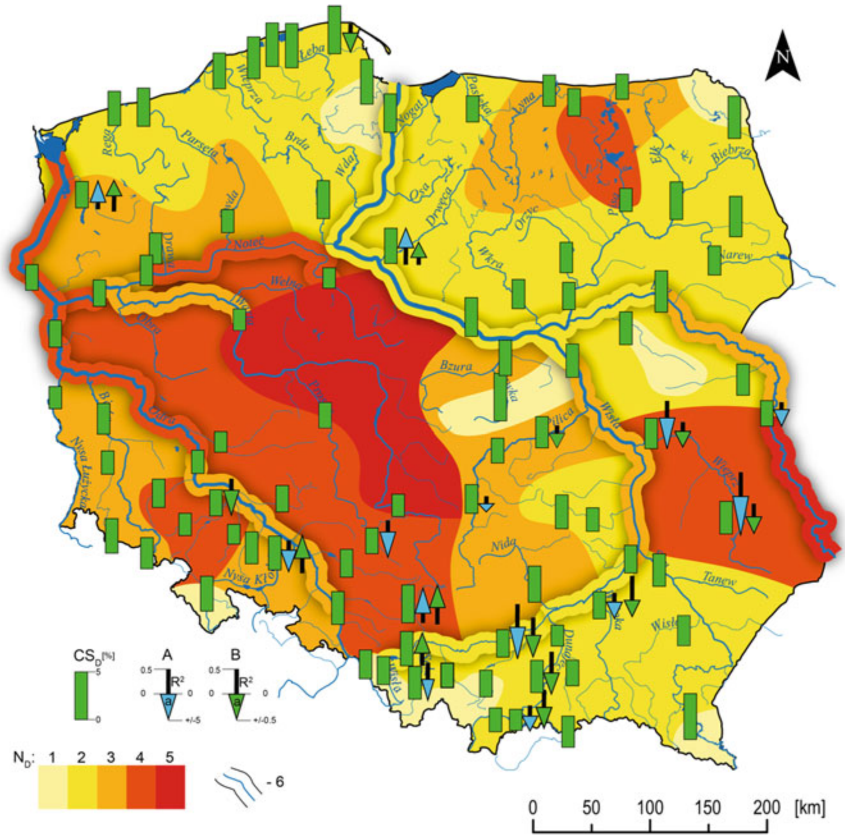


**Fig. 12.3** Spatial differentiation of selected hydrological drought estimators in Poland (1984–2015). Mean annual number of days with hydrological drought ($N_D$) (days): 1 – 121–135, 2 – 136–150, 3 – 151–165, 4 – 166–180, 5 – 181–195; 6 – $N_D$ changes in larger transit rivers (outside the map scale), $CS_D$ – mean annual coefficient of severe drought contribution (%); statistically significant ($\alpha = 0.05$) linear trend in multiannual course of annual number of days with hydrological drought (A) and the coefficient of severe drought contribution (B), a – trend line slope, $R^2$ – coefficient of determination, arrow direction denotes positive (up) or negative (down) sign of the slope

As mentioned in the statement opening this chapter, it was assumed that river low flow occurrence indicates the development of the hydrological drought in the catchment. Drought identification criteria were as follows:

- *Events of hydrological drought per year*, if the number of days with low flow ($Q_{70\%}$) exceeded 90 in a given hydrological year,
- *Events of hydrological drought per month,* if the number of days with low flow ($Q_{70\%}$) exceeded 10 in a given month.

Finally, for each of 87 investigated catchments the study identified the years and months with hydrological drought described by: the number of days with hydrological drought ($N_D$), the volume of drought streamflow deficit during drought ($V_D$), and a coefficient of severe hydrological drought contribution calculated as a quotient of severe streamflow deficit and total streamflow deficit during drought:

$$CS_D = \frac{VS_D}{V_D} \cdot 100\% \tag{12.2}$$

where:

$CS_D$ coefficient of severe hydrological drought contribution (%),
$VS_D$ volume of severe streamflow deficit during drought ($m^3$),
$V_D$ volume of total streamflow deficit during drought ($m^3$).

A comprehensive assessment of the hydrological drought at the country-wide scale required a definition of spatial measures that enabled a comparative analysis on a multiannual scale. The first measure is a range of hydrological drought that indicates the part of the country affected by hydrological drought in a given year or month [21]:

$$R_D = \frac{\sum A_D}{\sum A} \cdot 100\% \tag{12.3}$$

where:

$R_D$ a range of hydrological drought (%),
$\sum A_D$ total area of the catchments affected by the drought ($km^2$),
$\sum A$ total area of all investigated catchments ($km^2$).

Relative discharge deficits for individual low flow periods in a catchment (RVn) may be used to work out this deficit associated with drought ($RV_D$), which also serves as an estimator of the drought severity. The weighted average can then be used to calculate the hydrological drought severity index for entire Poland in monthly or yearly intervals [21]:

$$S_D = \frac{\sum_{i=1}^{N} (RV_{Di} \cdot A_i)}{\sum_{i=1}^{N} A_i} \tag{12.4}$$

where:

$S_D$ hydrological drought severity index (%),
$RV_{Di}$ a relative deficit of streamflow during a drought in catchment *i* (%),
$A_i$ catchment *i* area ($km^2$),
N number of catchments affected by hydrological drought.

## 12.3 Spatial Distribution of Hydrological Drought Estimators

A crucial element for the spatial analysis of hydrological drought structure in Poland is a distribution of the average annual number of days with drought (Fig. 12.4a). As per assumption made earlier in this chapter, the drought statistics were only calculated for the years in which the number of days with low flow exceeded 90. In the investigated group of catchments, average $N_D$, expressed as a median, equalled about 150 days. In half of the cases examined, the annual number of days with drought ranged between 140 and 162, while in extreme cases there were only 126 days or slightly more than half a year. The analyzed distribution was relatively symmetrical and close to normal. This proves a dominant role of hydroclimatic factors that determine the hydrological drought at the country level. Differences in river basin retention levels and specific factors shaping the water cycle become visible only at a regional or local scale.

The small average number of days with hydrological drought per year is typical of southern Poland (Fig. 12.3). The catchments of the Carpathian rivers feature high water resources, the prevalence of precipitation over evaporation in the water balance structure, and high rate of water exchange within the active exchange zone. As a result, hydrological droughts are rare in this region and are usually a consequence of a series of dry years. Hydrological droughts in the Sudetes last a bit longer. The average annual number of days with drought may reach up to half a year. The main reason for this is a change in the water balance structure manifested by an increased contribution of evaporation and declined supply from precipitation.

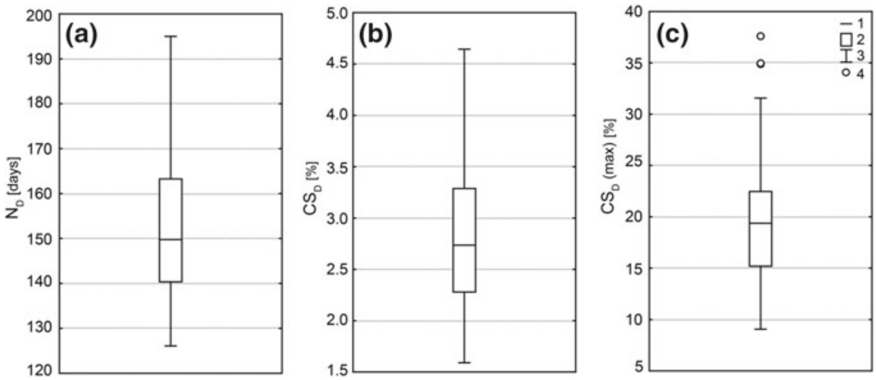


**Fig. 12.4** Distribution of selected hydrological drought parameters in Poland (1984–2015). **a** – mean annual number of days with hydrological drought, **b** – mean annual coefficient of severe drought contribution, **c** – maximum annual coefficient of severe drought contribution, 1 – median, 2 – variability range limited by the first and third quartile, 3 – non-outliers within the first interquartile range, 4 – outliers exceeding the first interquartile range

In the belt of highlands and lowlands, south of the Noteć and latitudinal section of the Vistula and the Bug, the average duration of hydrological drought enhances markedly. This zone is additionally separated by a longitudinal transect along the first-order watershed divide isolating the Vistula and the Oder basins (Fig. 12.3). West of this line, the duration of low flows in the years with hydrological drought reached five to six months, and its spatial variability was negligible. This indicates a similar water balance structure, hardly beneficial for water management, and poor water resources that are due to low retention capability of hydrogeological structures. The eastern part of the analyzed area is much more diverse. It harbours catchments with the small annual number of days with drought in the Świętokrzyskie Mountains as well as the basin of the Wieprz, where droughts last up to 178 days. This is associated with a slow rate of groundwater recharge in well-fissured carbonate rocks of the Lublin Upland. Within the lakeland regions, the average annual number of days with hydrological drought is shortened and usually does not exceed 150. This is obviously due to increased rainwater supply in the moraine elevation zone and the inflow of wet polar-marine air masses from the north-west sector. Interestingly, in the catchments with flow-through lakes of considerable size (e.g. of the Pisa or the Łyna), the average number of days with hydrological drought increases up to 180. This is probably due to enhanced evaporation from the water surface and not too large retention capacity of such lake harbouring catchments.

Severe hydrological drought markedly disturbs the functioning of facilities and water management systems. It is caused by a loss of seasonally renewable water resources and often results in the degradation of water-dependent ecosystems. Riverbeds then contain limited amounts of water supplied by groundwater reservoirs renewed in the multiannual cycle. Prolonged severe hydrological drought causes gradual drying of ever-larger watercourses. This phenomenon was assessed based on an annual number of days with low flow below $Q_{95\%}$, assumed as the severe drought estimator. The contribution of streamflow deficit during a severe drought in the total volume of the deficit during drought ($CS_D$) provided data necessary for the analysis of the structural properties of these events.

Average annual coefficient of severe droughts contribution in Poland equals about 2.7% (Fig. 12.4b). Variability of the parameter is small, as half of the values oscillating around the median fall within a relatively narrow range between 2.3 and 3.3%. The empirical distribution of the parameter is close to normal, which proves a stationary character of severe drought formation at the country-wide level. In a significant number of cases, the coefficient of severe droughts was inversely proportional to an annual number of days with hydrological drought (Fig. 12.3). This indicates some limitations in the development of this drought phase determined mostly by hydrogeological conditions. The coefficient of severe droughts contribution in the Carpathian catchments is close to the average for Poland but also more diversified. These catchments show a lower importance of severe droughts in the rivers below dam reservoirs (guaranteed flow), and variable $CS_D$ determined by the severity of winter hydrological droughts and variable retention capacity of the catchments that depends on geostructural and geofiltration factors. The above is true also for the Sudeten catchments, except for lower importance of winter droughts. The catchments of the western part of the lowland belt show a small and spatially variable contribution of severe droughts. In the rest of the country, severe hydrological droughts play a vital role in catchments that discharge water directly into the sea. However, considering a relatively efficient precipitation supply and favourable structure of the water balance in the coastal zone, water management should not be seriously affected by severe hydrological droughts.

The considerations presented above refer to a typical year and may differ from a situation when after a series of dry years (see Sect. 12.4) a particularly severe hydrological drought appears and causes damage to the environment and serious losses in the water management. This problem was assessed based on the maximum observed coefficients of severe drought contribution (Fig. 12.4c). The average maximum $CS_D$ in relation to a typical year increased by seven times (19.7%). The distribution of the analyzed variable shows outliers that indicate particularly strong effects of severe droughts on hydrological systems (above 35%: the San, the Rawka, the Łeba). As these catchments represent different geographical regions (mountains, lowlands, coastal areas), it may be hypothesized that extremely severe hydrological droughts strongly depend not only on hydrometeorological conditions but also local catchment-related factors and result from both natural phenomena and human activities.

The process of hydrological drought development follows a slightly different pattern along larger transit rivers (Fig. 12.3). The average annual number of days with hydrological drought in the upper course of the Vistula is mainly determined by its Carpathian tributaries. Below the entry of the San, the number of such days increases to 165 per year, but this does not reflect the features of drought in autochthonous catchments of direct tributaries of the middle Vistula section. Only after the entry of the Narew and the Bug, the number of days with hydrological drought drops back to 150 and remains at this level until the Vistula mouth thanks to gradual increment in water resources along with the growing basin area. Despite the relatively low value of $N_D$ estimated for the Vistula, the contribution of hydrological droughts is pretty high and can periodically disturb water management. A reverse situation occurs for the Oder. An average number of days with hydrological drought rises along the river course and is determined by its right bank lowland tributaries and droughts developing in the catchment of the Warta. The effects of these factors are so strong that the increase in water resources of the basin seems only a secondary factor determining the duration of hydrological droughts along the Oder.

The analysis of the hydrological drought duration and the contribution of severe droughts was supplemented by verification of the multiannual variability of these parameters against a systematic component. To this end, the linear trends verified with Student's t-test were identified at the significance level $\alpha = 0.05$ (Table 12.1, Fig. 12.3). Interestingly, 11 out of 14 significant, multiannual trends of an annual number of days with hydrological drought had a negative sign. These trends occurred in the selected mountain and upland catchments and indicated gradual mitigation of periods with water deficits within the investigated period. The trends with the best fit ($R^2$: 0.28–0.44) appeared in the rivers where large dam reservoirs were built.

**Table 12.1** Parameters of significant linear trends in the annual series of selected hydrological drought estimators

| River | Water-gauge | Annual number of days with hydrological drought ($N_D$) | | Coefficient of severe drought contribution ($CS_D$) | |
|---|---|---|---|---|---|
| | | a | $R^2$ | a | $R^2$ |
| Nysa Kłodzka | Skorogoszcz | −3.465 | 0.173 | 0.382 | 0.253 |
| Bystrzyca | Jarnołtów | −4.146 | 0.191 | – | – |
| Liswarta | Kule | −4.211 | 0.195 | – | – |
| Ina | Goleniów | 3.366 | 0.131 | 0.245 | 0.248 |
| Reda | Wejherowo | – | – | −0.303 | 0.149 |
| Vistula | NowyBieruń | – | – | 0.327 | 0.218 |
| Przemsza | Jeleń | 4.149 | 0.168 | 0.378 | 0.280 |
| Soła | Oświęcim | −3.504 | 0.275 | – | – |
| Raba | Proszówki | −5.622 | 0.404 | −0.360 | 0.326 |
| Dunajec | Krościenko | −2.278 | 0.165 | −0.351 | 0.293 |
| Dunajec | NowySącz | – | – | −0.361 | 0.376 |
| Wisłoka | Mielec | −2.472 | 0.140 | −0.276 | 0.410 |
| Wieprz | Krasnystaw | −7.049 | 0.441 | −0.265 | 0.211 |
| Wieprz | Kośmin | −6.068 | 0.362 | −0.303 | 0.200 |
| Pilica | Przedbórz | – | – | −0.163 | 0.150 |
| Pilica | Białobrzegi | −2.900 | 0.144 | – | – |
| Bug | Włodawa | −3.296 | 0.151 | – | – |
| Drwęca | Elgiszewo | 3.921 | 0.343 | 0.302 | 0.150 |

Significance level: $\alpha = 0.05$, a – slope coefficient of the trend line, $R^2$ – determination coefficient

Water management at these facilities allows for alleviating the effects of hydrological drought, as manifested by a significant tendency to the reduced number of days with drought. A similar observation is true for the coefficient of severe droughts contribution, which systematically decreases as a result of guaranteed flow generated by these reservoirs. However, in the rivers downstream of the reservoirs, in which municipal functions predominate (e.g., the Vistula – Nowy Bieruń, the Nysa Kłodzka – Skorogoszcz), where water resources are stored and transported over natural catchments, significant positive trends were noticed for the coefficient of severe droughts contribution with relatively high fit ($R^2 = 0.3$). Spatial analyses do not reveal dense or ordered zones with significant multiannual trends for hydrological drought estimators. It can, therefore, be assumed that the observed trends do not have a hydroclimatic background and are triggered by local factors, mainly related to water management.

## 12.4 Multiannual Variations

In multiannual perspective, the average annual number of days with hydrological drought in Poland ranged from 104 to 183 (Fig. 12.5). The longest droughts occurred in the years 1990–1994 when long-term and severe low flows in rivers were observed [7], caused by a series of dry years [28]. The lowest number of days with hydrological drought was noticed in 1998 and 2010 when water levels in Polish rivers were exceptionally high, resulting in catastrophic floods in some catchments. An extreme year in this respect was 1997, when droughts were followed by particularly high flood waves with peak flows exceeding 0.001 probability of exceedance (so-called 1,000-year flood) at some water gauges.

The groups of dry and wet years are also visible along the course of hydrological drought range index (Fig. 12.5). The periods with the large annual number of days with hydrological drought are usually characterized by an extensive range of the phenomenon. However, drought has never affected 100% of the analyzed area in one year for the entire period of the study. Droughts with the range exceeding 95% of the country area occurred in the years 1990–1994, 2003–2004, 2006 and 2012. The hydrological drought of the smallest range of 15% occurred in 2010.

Average annual index of drought severity in Poland ranged in the investigated multi-year period between 16.6 and 32.2% (Fig. 12.5). Years with high drought

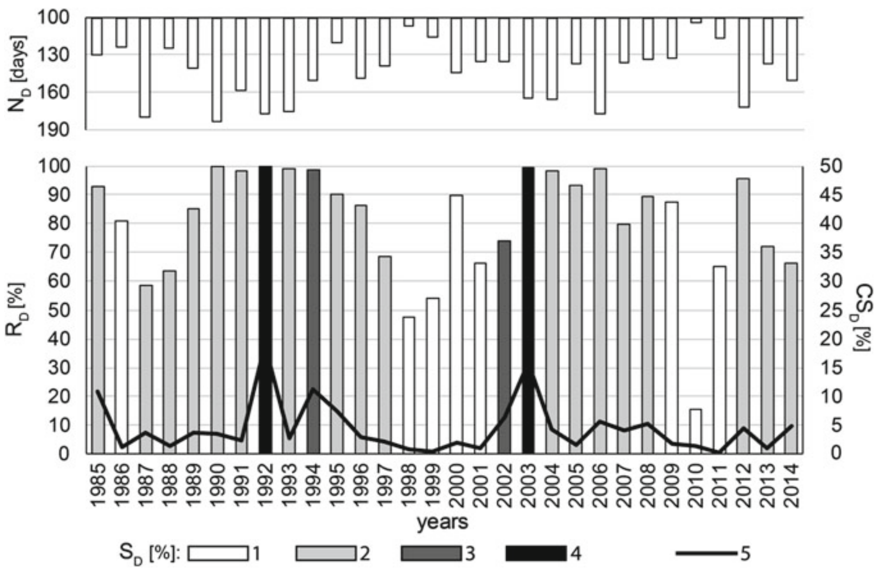


**Fig. 12.5** Multiannual course of selected hydrological drought parameters in Poland. $N_D$ – mean annual number of days with hydrological drought, $R_D$ – range of hydrological drought, $S_D$ – hydrological drought severity index (%): 1 – 0–4, 2 – 5–10, 11–16, 17–21, 5 – $CS_D$ – coefficient of severe drought contribution; parameters $N_D$, $S_D$ and $CS_D$ were calculated based on weighted average where the weight was the catchment area (see Sect. 12.2)

severity index, in which the degree of drainage of catchment water resources available during low flow periods exceeded 30% usually constituted a core of a few-year long drought periods, e.g., 1990–1994, 2002–2006. Mild hydrological droughts ($S_D$ < 20%) occurred in 1986, 1998–2001 and 2009–2011. They were usually characterized by small range and lower than the average annual number of days with hydrological drought.

The index of severe drought contribution was a source of many interesting observations (Fig. 12.5). Its values in the multiannual period of investigation varied from 0.15 to 18.95% and were obviously the highest in the years with severe hydrological droughts (1992, 2003). However, in the remaining years, this relationship was not so clear and linear (Fig. 12.6a). The fit of the exponential function indicates that for mild droughts, a small increase in the number of days with severe drought triggers a rapid increase in the drought severity index. For severe droughts, a much larger increase in severe drought contribution is necessary for a similar spike in this metric. The course of the analyzed function may be of vital importance for water management as it demonstrates that mean annual drought severity index in Poland should not exceed 50%.

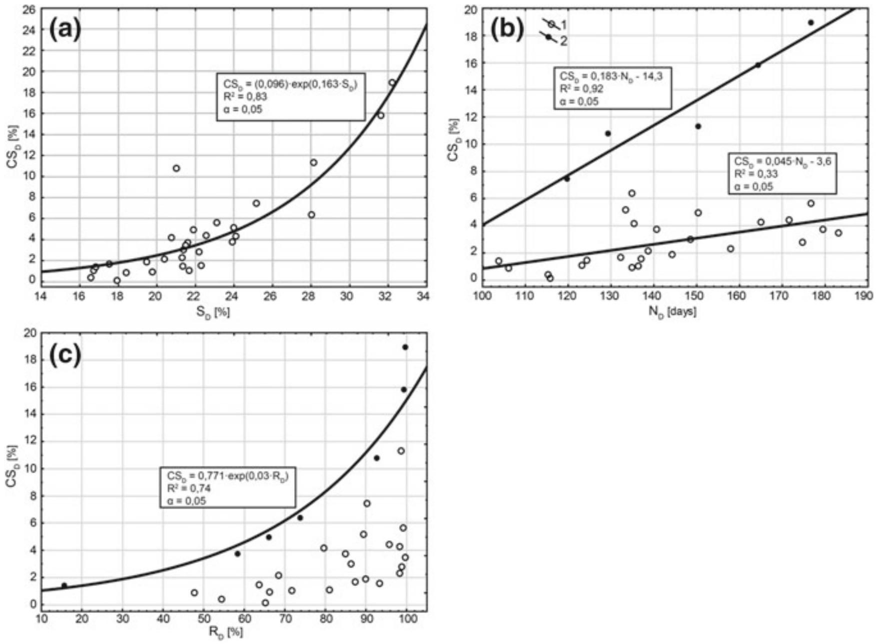


**Fig. 12.6** Regression dependencies between selected parameters of hydrological drought. $CS_D$ – coefficient of severe drought contribution; $S_D$ – hydrological drought severity index, $N_D$ – number of days with hydrological drought, $R_D$ – range of hydrological drought, α – significance level of an established regression equation; $R^2$ – coefficient of determination, 1 – function established for points without maximum values $CS_D$, 2 – envelope function of maximum $CS_D$ values

The contribution of severe droughts strongly correlates with total drought duration during the year (Fig. 12.6b). The resulting linear dependence does not show a good fit ($R^2 = 0.33$), which indicates a large impact of stochastic hydrometeorological conditions that affect the relationship. However, a strong linear dependence ($R^2 = 0.92$) could be observed for the envelope following the maximum points of severe drought contribution. This function indicates regional limitations of severe drought development in Poland and may be helpful in water management planning that considers the predicted annual number of days with hydrological drought. The severe drought contribution coefficient partly correlated with drought range index (Fig. 12.6c). Although graphic representation of the dependence shows a cloud of points impossible to approximate with a linear function, the envelope composed of points with a maximum contribution of severe droughts can be described with the exponential equation of high degree of fit ($R^2 = 0.74$). In practice, it is possible to determine regional limits of the maximum coefficient of severe droughts contribution in relation to the area affected by hydrological drought.

The multiannual course of the analyzed parameters did not reveal any linear trends statistically significant at $\alpha = 0.05$. It can, therefore, be concluded that in Poland, the long-term variability of hydrological drought parameters depends primarily on the natural fluctuation of hydroclimatic conditions.

## 12.5 Seasonal Variations

### *12.5.1 Monthly Variability*

Dynamics of the hydrological system reveals significant variability of the water balance structure and the size of water resources within the seasonal cycle. Monthly intervals are basic units for determining disposable resources for water management and assessing water needs at a regional and national scale. This section provides a statistical analysis only for the months in which the number of days with hydrological drought exceeded 10 (see Sect. 12.2).

Monthly distribution of the average number of days with hydrological drought reflects a simple, seasonal variability (Fig. 12.7). Between November and March, this parameter systematically decreases until the minimum of 18 days. This is the effect of a gradually weakening evapotranspiration determined by temperature changes and disappearance of vegetation. The gradually decreasing drought severity index (from 8.6 to 2.8%) confirms the hypothesis that in recent years, catchment water resources are recharged in winter. This is mainly due to milder weather conditions during this season, resulting in high rainfall retention and relatively small evapotranspiration [7]. Winter hydrological droughts demonstrate relatively stable range (20–25%), and the local maximum of the severe drought contribution coefficient falls in January. This indicates stability of winter droughts in selected mountain catchments in which regular and periodic storage of water in the snow cover is often intensified by frost

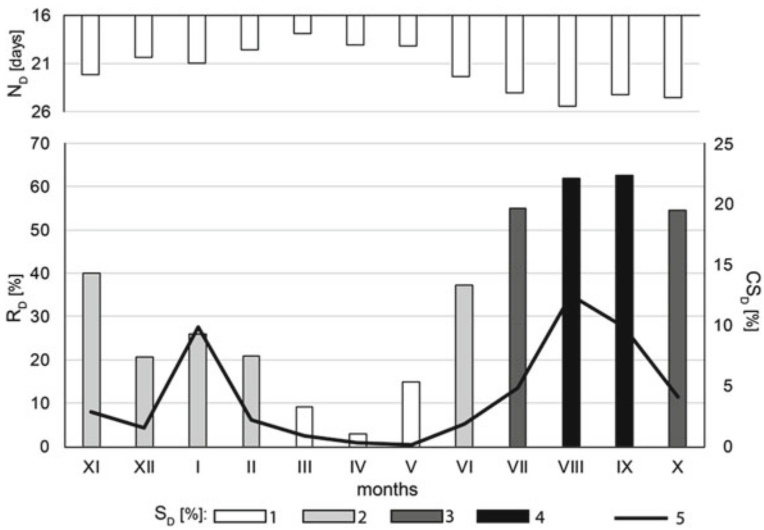


**Fig. 12.7** Seasonal course of selected hydrological drought parameters in Poland. $N_D$ – mean monthly number of days with hydrological drought, $R_D$ – mean monthly range of hydrological drought, $S_D$ – mean monthly hydrological drought severity index (%): 1 – 0–4, 2 – 5–10, 11–16, 17–21, 5 – $CS_D$ – mean monthly coefficient of severe drought contribution; parameters $N_D$, $S_D$ and $CS_D$ were calculated based on a weighted average where the weight was the catchment area (see Sect. 12.2)

penetration into the riverbeds. Observations of multiannual variability of drought estimators for the autumn months on the example of November revealed a tendency for grouping the years in drought periods typical of the entire multi-year period (Fig. 12.8a). The average degree of drought severity and its duration indicates that the majority of these episodes occur as the continuation of prolonged summer hydrological droughts (see Fig. 12.8d). In dry periods, the range of November droughts falls between 40 and 95%, while in wet ones it is marginal to complete cessation as in, e.g. 1999. In winter months (January), the range of more extensive droughts varies between 50 and 70%, while smaller droughts cover below 20% of the country area (Fig. 12.8b). Droughts of longer duration and considerable coefficient of severe drought contribution occurred fairly regularly as a result of long, snowy and frosty winters. In the years following such a winter, Poland experienced high water levels in rivers that often transformed into catastrophic floods, e.g., in 1994, 1997, 2010.

In the spring (March–May), hydrological droughts are rare and of low intensity due to snow melt and accompanying floods (Fig. 12.7). Moreover, vegetation that only begins to develop does not generate intense evapotranspiration. A good illustration of this situation is a multiannual course of hydrological drought parameters for April (Fig. 12.8c). In this month, droughts appeared on average every two or three years, although there were also a few year periods without drought. The number of days

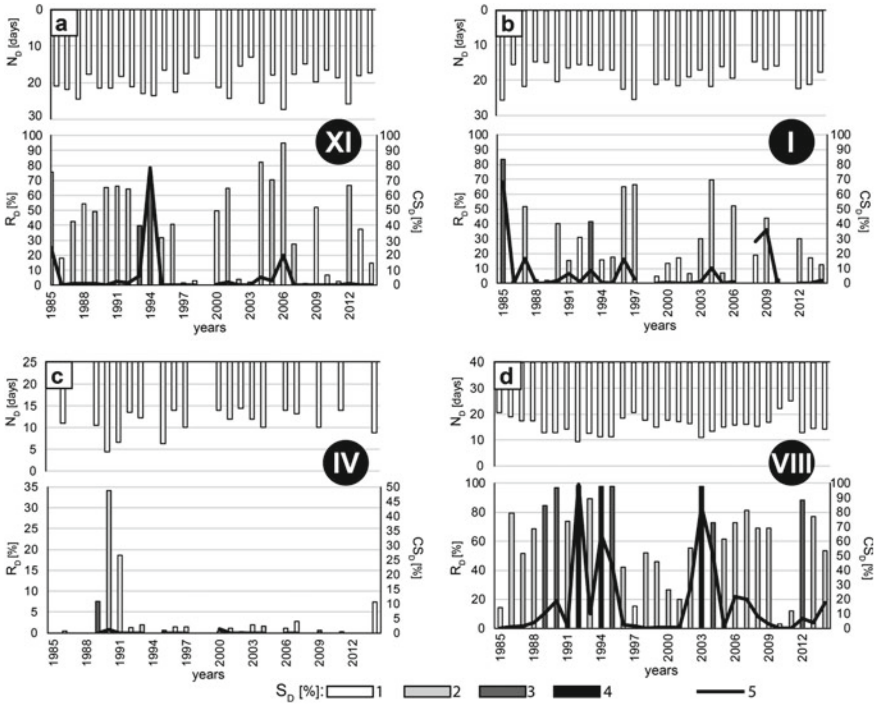


**Fig. 12.8** Multiannual course of hydrological drought parameters in selected months. **a** – November, **b** – January, **c** – April, **d** – August, other symbols as in Fig. 12.7

with drought rarely exceeded 15, and usually included only a few percent fraction of the investigated area.

Severe and extensive hydrological droughts usually develop in the summer and early autumn (July–October), while June is a transitional month that may significantly prolong drought duration in the years with dry spring and summer (Fig. 12.7). A maximum number of days with drought and the highest coefficient of severe drought contribution occurs in August ($N_D$ = 25.5 days, $CS_D$ = 12.5%), which indicates high stability of evapotranspiration conditions that determine water deficits in this period. Summer and autumn droughts also belong to the most extensive ones ($R_D$: 54.5–62.5%) and are characterized by high or very high severity that is due to the high homogeneity of factors that determine drought properties in the summer half of the year. In the month with the most intense hydrological drought throughout a year (August), the number of days with drought only occasionally falls below 20 (Fig. 12.8d). Droughts of extensive range (60–100%) and high severity occurred in the years 1986–1995, 2003–2009 and 2012–2013, and accounted for about two-thirds of the investigated multi-year period. The years 1996–2002 were a period with droughts moderate in terms of range and intensity. A clear grouping of dry and wet years depends not only on precipitation but also results from the ongoing recession of groundwater resources in the catchment. Depletion and recharge of these water reserves show huge inertia that causes droughts of similar properties to group in a few year-long periods.

### *12.5.2 Degree of Seasonality and Concentration Date of Hydrological Drought*

The degree of hydrological drought severity depends mainly on hydrometeorological conditions in the period preceding its occurrence. Deficit of water resources may be determined by seasonal anomalies associated with a lack of supply in typical time of alimentation or multiannual disturbances evoked, e.g. by a series of dry years. Both groups of factors overlap in a random and practically inseparable way, making droughts and low flows highly variable events with unpredictable frequency and intensity.

This strong irregularity in the appearance of drought streamflow deficits considerably hampers seasonal analyses based on time series analyzed in monthly steps (see Sect. 5.1). A solution to this problem may be applying characteristics that describe the seasonal variability comprehensively. The variability of the annual course of drought streamflow deficits and their concentration date may be identified using angular measures introduced to the literature by Markham [29]. Originally, they served to analyze seasonal variability of precipitation in the US, but following a few methodological transformations, two seasonality measures of hydrological drought were proposed: seasonality index (SI) and seasonal concentration date index (CI) [7].

Both measures assume that monthly volume of drought streamflow deficit is represented by a vector ($r_i$) of a length proportional to the volume of this deficit and an angle of inclination ($\alpha_i$) depending on the position of the middle of a given month relative to the beginning of the hydrological year:

$$\alpha_i = \frac{360 \cdot S}{365} \tag{12.5}$$

where:

S number of days between the beginning of the hydrological year and the middle of the month.

As a result, 12 vectors are obtained for which a resultant vector R of the module |R| and direction ω is determined (Fig. 12.9). The quotient of the resultant vector |R| and the total length of the partial vectors $|r_i|$ allows for the calculation of the seasonality index SI:

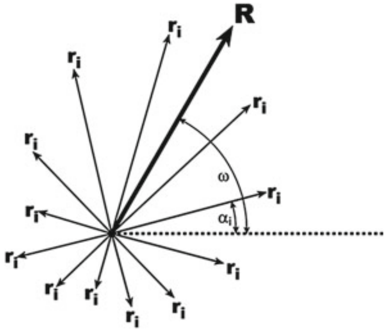


**Fig. 12.9** Construction of Markham's seasonality measures. $r_i$ – vector representing drought streamflow deficit per month *i*, R – resultant vector for vectors $r_i$, $\alpha_i$ – angle representing the middle of the month in relation to the beginning of hydrological year, ω – angle indicating concentration date of hydrological drought in relation to the beginning of hydrological year

$$SI = \frac{|R|}{\sum_{i=1}^{12} |r_i|} \cdot 100\% \tag{12.6}$$

The obtained measure assumes values between 0 and 100% and increases along with the rise of the degree of seasonality for hydrological drought. A result equal 0% may indicate not only a total uniformity of drought streamflow deficit over the year but also a situation when hydrological drought occurs only in two opposite months (e.g., November and May). Both cases are extreme and theoretical but point to the need for careful interpretation of the calculation results. The angle of inclination of the resultant vector R (ω) serves as an estimator of hydrological drought concentration date (Fig. 12.9), and the value of the seasonal concentration date index (CI) is calculated according to the following formula:

$$CI = \mathrm{arctg}\left(\frac{\sum_{i=1}^{12} |r_i| \cos\alpha_i}{\sum_{i=1}^{12} |r_i| \sin\alpha_i}\right) \cdot \frac{365}{360} \tag{12.7}$$

The final value, usually represented by a date, indicates the resultant time of concentration of drought streamflow deficits which does not always coincide with the month of their maximum intensity [7, 29, 30]. Multiannual stability of the concentration date for hydrological drought was evaluated using the seasonal concentration date frequency coefficient C. The measure indicates the percentage contribution of the number of years in which the hydrological drought concentration date occurred in a month of typical seasonal concentration date in relation to the total number of years in the multi-year period.

In most catchments investigated in this study, the hydrological drought concentration date occurred in the summer-autumn period (Fig. 12.10). Differentiation of CI revealed a clear spatial order (Fig. 12.11). In the Carpathian catchments, the

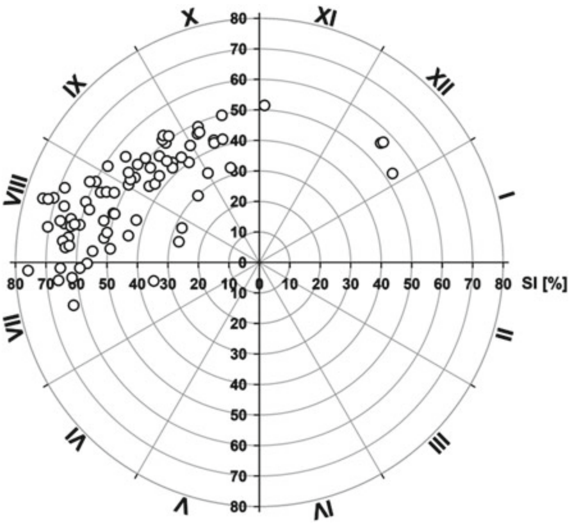


**Fig. 12.10** Position of the tips of the vectors denoting seasonality index and the index of seasonal concentration date of hydrological drought in the investigated catchments (1985–2014)

latest CI (second half of December) occurs in the upper part of the Dunajec catchment (Fig. 12.10). This means that the streamflows deficits during winter low flow markedly prevail over those from the warm half-year. This feature of flow seasonality is maintained in the Dunajec until its mouth, but entering of consecutive tributaries moves the seasonal concentration date in its lower section back to the beginning of November. The increased importance of summer drought streamflow deficits means that in the majority of remaining Carpathian tributaries of the Vistula, the hydrological drought concentration date occurs in the first half of October, and for the San even in the second half of September.

In the upper section of the Vistula, above the mouth of the Przemsza, the concentration date falls already in July. This is due to the effects of the Goczałkowice Reservoir, in which water reserves for municipal needs are renewed mainly in the spring and during summer floods. As a result, low flows are observed downstream of the dam in the periods of typical discharge increase, which modifies flow regimes of this section of the river [31]. Catchments of the rivers dominated by one genetic type of low flows (e.g., the Dunajec and the San systems) show relatively stable hydrological drought concentration date within any multi-year period. Frequency coefficients of the seasonal concentration date C in these catchments reach 40–50%. In the other Carpathian rivers, the dynamics of summer and winter low flows remain very high. This results in relatively low values of the C coefficient – in extreme cases, the seasonal concentration date in a typical month of low-flow occurs only once every 7 years (C $\approx$ 15%). The seasonality index of hydrological drought in the Carpathians is pretty stable and fits a narrow interval of 40–55%. This indicates a high similarity of hydrometeorological and hydrogeological conditions that determine the

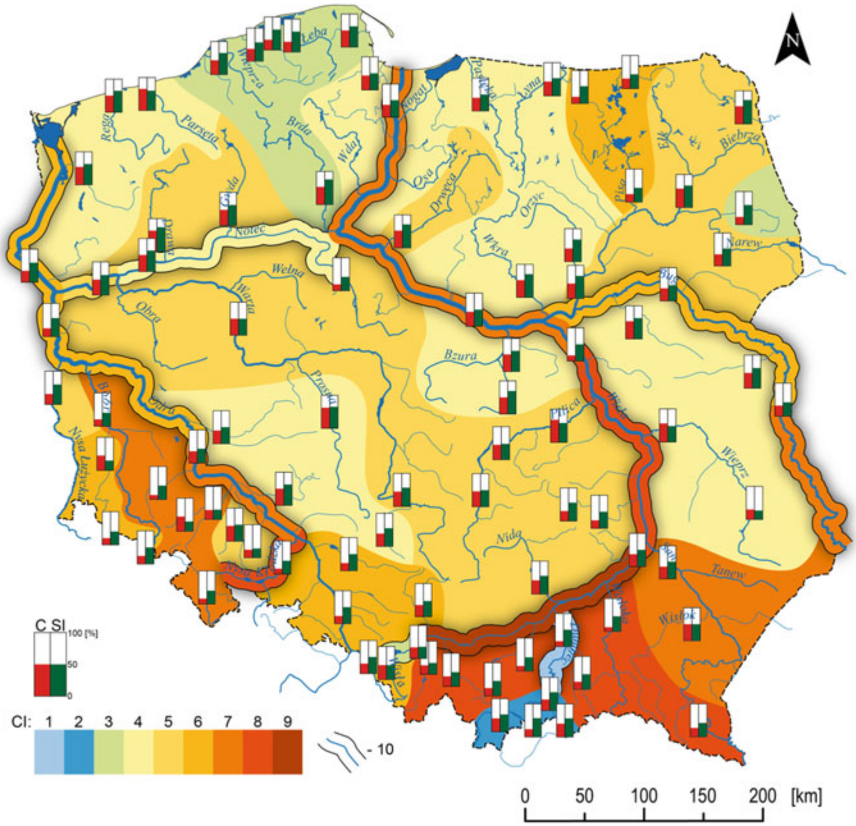


**Fig. 12.11** Seasonal concentration date of hydrological drought in Poland (1985–2014). CI – index of concentration date of hydrological drought: 1 – 1–15 November, 2 – 16–31 December, 3 – 16–31 July, 4 – 1–15 August, 5 – 16–31 August, 6 – 1–15 September, 7 – 16–30 September, 8 – 1–15 October, 9 – 16–31 October; 10 – CI changes in larger transit rivers (outside the map scale), the legend colour according to the periods: 1–9; C – frequency coefficient of the seasonal concentration date, IS – seasonality index of hydrological drought

occurrence of river low flows in the region as well as recession and renewal of water resources. The only exceptions are the Soła and a section of the upper Vistula, where water management activities in the Soła cascade and the Goczałkowice Reservoir lower SI down to 33–35%.

Typical concentration date of hydrological drought in the Sudeten rivers precedes that in the Carpathian watercourses by ca. 15 days. However, mean CI in the rivers of the Kłodzko Valley, the Karkonosze Mountains, and the Kaczawskie Mountains falls in the second half of September, thus suggesting a higher contribution of winter low flows than in the other watercourses of the region. A delay in the seasonal concentration date in the Nysa Kłodzka due to the effects of the Otmuchów and Nysa reservoirs is also clearly visible. These effects are strong enough to cause a similar delay in the Oder. Frequency coefficients of CI in the Sudetes are more variable than in the Carpathians and range from 13 to 45%. The Sudeten rivers also show slightly higher spatial diversity of the hydrological drought seasonality index (30–60%) than the Carpathian ones. Low SI is typical for cross-sections located on the rivers with abundant base flow from capacious aquifers (the Oława, the Bystrzyca) or placed downstream of the dam reservoirs (the Nysa Kłodzka).

In most upland and lowland rivers, seasonal concentration date of hydrological drought occurs in August (Fig. 12.11). CI dates from the first half of this month are typical for rivers the water resources of which are slightly smaller, e.g., for right tributaries of the middle Oder, left tributaries of the upper and middle Warta, the Bzura system, the Vistula and the Bug inter-fluve area, and some rivers of the lake districts. Rapid depletion of small water resources results in a relatively early seasonal concentration date of hydrological drought in these rivers. In lake systems with high lake density and a large number of flow-through and outflow lakes, the drought concentration date occurs slightly later (the Pisa, the Drwęca, the Gwda, the Drawa, the upper Noteć) [32]. In the coastal rivers, CI indicates a relatively early seasonal concentration date of hydrological drought, particularly in the eastern part of the region. This is directly linked to an early seasonal concentration date of total flow [33].

Seasonal concentration date of hydrological drought in lowland rivers is highly stable for a multi-year period. The reason for this is the dominance of summer half-year low flows. At the same time, seasonality of hydrological drought is high or very high due to the high similarity of factors determining the formation and severity of the low flows. In many lake and upland river systems characterized by a large contribution of groundwater flow, the seasonal concentration date is also stable for a multi-year period, as permanent base flow effectively buffers the impact of random precipitation events. This is the reason why upland catchments with the large and stable contribution of groundwater flow (e.g., the Wieprz) feature very low seasonality indices of hydrological drought.

The situation may differ in some large transit rivers, in which low flow trends depend on characteristic features of their tributaries (Fig. 12.11). Mean multiannual seasonal concentration date of hydrological drought for the Vistula downstream of the Goczałkowice Reservoir depends on the dynamics of the Carpathian tributaries and typically falls on 16 October. Downstream of the San entrance, CI occurs 10 days earlier, and from the mouth of the Bug and the Narew until the mouth of the Vistula, the date is shifted to 22 September. The difference in mean seasonal concentration date between the lower Vistula and its autochthonous tributaries may even exceed two months. Slightly smaller differences are observed for the Oder and the Bug, where the gradual impact of subsequent tributaries is visible, but the distinctiveness of low-flow regime is maintained until the estuaries. Although the middle and lower Noteć "inherits" low flows from the upper part of the river system and tributaries from catchments of high lake density, its seasonal concentration date of hydrological drought falls relatively early. In the transit rivers, the frequency coefficient C along the river course is lowered when low flows in the tributaries are not synchronized with the low flows of the main river [31]. Such situations happen for the Vistula downstream of the San entrance and for the Oder after it is joined by the Bóbr and the Nysa Łużycka and then the Warta.

## 12.6 Summary and Conclusions

The study demonstrates that employing low flows as indicators of hydrological drought development seems promising. The adopted identification and separation criteria allowed for unambiguous isolation of mild and severe hydrological droughts in Poland in the years 1985–2014. Transformation of the parameters describing the duration and the relative deficit of streamflow and the share of the catchment in the entire investigated area enabled the assessment of hydrological droughts in terms of their duration, severity, and range. It also allowed for pointing out periods differing in the intensity of the assessed parameters. The evaluation of seasonal and multiannual variability, as well as analysis of genetic relationships between selected estimators of hydrological drought, provided new and valuable cognitive insights and made it possible to identify a group of factors the determine drought development. Practical conclusions, especially those concerning regional barriers for development and regularities of the duration and range of hydrological drought can significantly expand water management activities aimed at mitigation of drought effects at the national and regional scale.

The analysis proves that both the seasonal concentration date and intensity of hydrological drought in Poland show significant and multidirectional variability. In the mountain rivers, low-flow regimes are significantly affected by genetically different summer and winter low flows (CI – September-December), while the rest of the country is dominated by summer half-year deficits (CI – July–September). Apart from hydrometeorological conditions, seasonal distribution of hydrological drought is also determined by local factors associated with water resources and the rate of their exchange in the hydrologically active zone and with some aspects of water management. Large transit rivers gradually change the features of their low-flow regime along with the entrance of successive tributaries but retain their regime specificity up to the estuary. Allochthonous features of low-flow regime inherited from the upper part of the basin, and larger tributaries are present in the regimes of the Vistula, the Oder, the Bug, the Noteć, the Nysa Kłodzka and the Dunajec. The high degree of hydrological drought seasonality occurs when its average seasonal concentration date falls in the summer months (Fig. 12.10). When the CI is shifted towards autumn months, the seasonality index decreases as droughts of the winter half-year become more and more important.

## 12.7 Recommendations

Presented results of analyses have finished some stage of the study. Knowledge of hydrological droughts spatial pattern and time variability in Poland as well as their determinants allows to use some conclusions in water management planning and water resources assessment. It also might effectively support the tools and strategies of optimal reduction of drought results, its prevention, and prediction.

When the defined scientific problems have been solved, new questions appeared. It is possible to express it in one statement: does present level of knowledge allow to construct the regional model of hydrological drought? This does not concern operational active model but the procedure predicting general level of drought streamflow deficit expected in annual or half-yearly advance. In authors opinion, features of investigated time series and identified regularities are so promising that the trial of such study might be realized soon.

## References

1. Maunder WJ (1992) Dictionary of global climate change. Chapman & Hall, New York
2. Nagarajan R (2009) Drought assessment. Springer, Dordrecht
3. Lloyd-Huges B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592
4. Łabędzki L (2007) Estimation of local drought frequency in central Poland using the standardized precipitation index SPI. Irrigat Drainage 56:67–77
5. Łabędzki L, Bąk B (2004) Zróżnicowanie wskaźnika suszy atmosferycznej SPI w sezonie wegetacyjnym w Polsce (differentiation of the atmospheric drought index SPI in the vegetation period in Poland). Woda-Środowisko-Obszary Wiejskie 11(2a):111–122
6. Somorowska U (2016) Changes in drought conditions in Poland over the Past 60 years evaluated by the standardized precipitation-evapotranspiration index. Acta Geophys 64(6):2530–2549
7. Tomaszewski E (2012) Wieloletnia i sezonowa dynamika niżówek w rzekach środkowej Polski (multiannual and seasonal dynamics of low-flows in rivers of central Poland). Wyd. Uniwersytetu Łódzkiego, Łódź
8. Wilhelmi OV, Hubbard KG, Wilhite DA (2002) Spatial representation of agroclimatology in a study of agricultural drought. Int J Climatol 22:1399–1414
9. Dingman SL (2002) Physical hydrology. Prentice Hall, New Jersey
10. Hisdal H, Tallaksen LM, Peters E, Stahl K, Zaidman M (2001) Drought event definition. In: Demuth S, Stahl K (eds) Assessment of the regional drought impact of droughts in Europe. Institute of Hydrology, University of Freiburg, pp 17–26
11. Sene K (2010) Hydrometeorology. Forecasting and applications, Springer, Dordrecht-Heidelberg-London-New York
12. Wilhite DA (2005) Drought. In: Olivier JE (ed) Encyclopedia of World Climatology. Springer, Dordrecht, pp 338–341
13. Jokiel P (1994) Zasoby, odnawialność i odpływ wód podziemnych strefy aktywnej wymiany w Polsce (groundwater resources, renewal and flow in the active exchange zone in Poland). Acta Geographica Lodziensia 66–67:1–236
14. Smakhtin VU (2001) Low flow hydrology: a review. J Hydrol 240:147–186
15. Tallaksen LM (1995) A review of baseflow recession analysis. J Hydrol 165:349–370
16. Laaha G (2002) Modelling summer and winter droughts as a basis for estimating river low flows. In: FRIEND 2002 – regional hydrology: bridging the gap between research and practice

(proceedings of the fourth international FRIEND conference held at Cape Town, South Africa, March 2002), IAHS Publ., vol 274, pp 289–295

17. Loon AF, van Lanen HAJ, van Hisdal H, Tallaksen LM, Fendeková M, Oosterwijk J, Horvát O, Machlica A (2010) Understanding hydrological winter drought in Europe. In: FRIEND 2010 – global change: facing risks and threats to water resources (Proceedings of the Sixth World FRIEND Conference, Fez, Morocco, October 2010), IAHS Publ., vol 340, pp 189–197
18. Pfister C, Weingartner R, Luterbacher J (2006) Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach. Hydrol Sci J des Sciences Hydrologiques, 51(5):966–985
19. Wilhite DA, Hayes MA, Knutson C, Smith KH (2000) Planning for drought: moving from crisis to risk management. J Am Water Resour Assoc 38(4):697–710
20. Tokarczyk T, Szalińska W (2018) Drought hazard assessment in the process of drought risk management. Acta Sci Pol Formatio Circumiectus 18(3):217–229
21. Kozek M, Tomaszewski E (2018) Selected characteristics of hydrological drought progression in the upper Warta river catchment. Acta Sci Pol Formatio Circumiectus 18(3):77–87
22. Tokarczyk T (2013) Classification of low flow and hydrological drought for a river Basin. Acta Geophys 61(2):404–421
23. Tomaszewski E (2011) Defining the threshold level of hydrological drought in lake catchments. Limnol Rev 11(2):81–89
24. Dębski K (1970) Hydrologia (Hydrology). Arkady, Warszawa
25. Hisdal H, Tallaksen LM, Clausen B, Peters E, Gustard A (2004) Hydrological drought characteristics. In: Tallaksen LM, van Lanen HAJ (eds) Hydrological drought. Processes and estimation methods for streamflow and groundwater. Developments in Water Science, vol 48, pp 139–198. Elsevier, Amsterdam
26. Ozga-Zielińska M (1990) Niżówki i wezbrania – ich definiowanie i modelowanie (droughts and floods – their definition and modelling). Przegl Geof 1–2:33–44
27. Yevjevich V (1967) An objective approach to definitions and investigations of continental hydrologic drought. Hydrology Paper, No. 23, Colorado State Univ., Fort Collins, Colorado
28. Stachý J (2011) Występowanie lat mokrych i posusznych w Polsce (1951–2008) (Wet and dry years occurrence in Poland (1951–2008). Gospodarka. Wodna. 8:13–321
29. Markham CG (1970) Seasonality of precipitation in the United States. Ann Assoc Am Geogr 60(3):593–597
30. Tomalski P, Tomaszewski E (2015) Metody, formuły i wzory obliczeniowe zastosowane w pracy (Methods, formulas and computational equations). In: Jokiel P (ed) Metody statystyczne w analizach hydrologicznych środkowej Polski (statistical methods in hydrological analyses of central Poland). Wyd, Uniwersytetu Łódzkiego, pp 215–272
31. Tomaszewski E (2017) Niżówki i susze (Low-flows and droughts). In: Jokiel P, Marszelewski W, Pociask-Karteczka J (eds) Hydrologia Polski (Hydrology of Poland). Wydawnictwo Naukowe PWN, Warszawa, pp 175–182
32. Tomaszewski E (2016) Impact of Lake Gopło on low-flow regime of the upper Noteć river. Limnol Rev 16(2):95–103
33. Bogdanowicz R (2009) Zasoby rzek Przymorza i ich zmienność (Water resources of coastal rivers and their variability). In: Bogdanowicz R, Fac-Beneda J (eds) Zasoby i ochrona wód. Obieg wody i materii w zlewniach rzecznych (Water resources and water protection. Water and matter cycling in river basins). Fundacja Rozwoju Uniwersytetu Gdańskiego, Gdańsk, pp 47–62