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SELECTED CHARACTERISTICS OF HYDROLOGICAL DROUGHT PROGRESSION IN THE UPPER WARTA RIVER CATCHMENT

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ABSTRACT

In the study, identification of hydrological drought was made, assuming that the low-flow period, which is a symptom of drought, is also a good estimator of its progression. The research was conducted in the upper Warta river catchment, for which the series of daily discharge for 12 gauging stations from the period 1971–2000 were available. The low-flow periods were identified on the basis of the constant threshold level, which corresponds to the 70th percentile of the flow duration curve ($Q_{70\%}$). For the identified low-flow episodes, parameters pertaining to its duration, streamflow deficit, and flow dynamics have been estimated. The established identification and separation criteria made it possible to assess the simple and compound hydrological droughts unambiguously. Transformation of characteristics related to low-flow duration, relative drought streamflow deficit as well as low-flows contribution in the total number of gauging stations resulted in the evaluation of hydrological drought in terms of its severity and range. The characteristics, which are estimators of hydrological drought progression and recession rate, made it possible to define the determinants of the studied phenomenon and its time variability.

Keywords: river low-flow, drought streamflow deficit, drought severity level, low-flows dynamics

INTRODUCTION

The hydrological drought is the most advanced form of the part of the hydrological cycle, which is determined by supply shortages related to the distribution of precipitation or snow and ice retention. The initial phases of the discussed process are related to the development of meteorological and soil drought, manifested by the lack of rainwater supply with a strong overdrying of the ground, preventing the effective recharge of groundwater resources. The aquifers of the hydrologically active zone are isolated from the water supply, but at the same time they are subject to linear and point drainage (of watercourses and springs). As a result, the groundwater level decreases (ground low-water), followed by the recession of surface water, which is usually in a hydraulic connection to groundwater (surface low-water). The rate of depletion of the resources of the active exchange zone in this period, called the dry weather phase, depends almost exclusively on the degree of filling of groundwater reservoirs (Jokiel 1994). During the growing season, the discussed process may be significantly increased by evapotranspiration, while in the wintertime, the recession of flow may be accelerated as a result of riverbed freezing process.

River low-flow, which is the last phase of the reaction to water supply deficits, is considered as a good indicator of the development of hydrological drought (Strzebońska-Ratomska 1994, Tokarczyk 2010). Generally, it is defined as the period of low flows (stages) in the river, or flows persisting in dry weather condi-

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tions (Dębski 1970, Smakhtin 2001). Further clarification of the definition of low-flows depends on the research approaches used. One of those approaches is the threshold level method (TLM), in which the identification of low-flow periods is based on the analysis of the flow hydrograph against a certain truncation level, determined on the basis of the selected characteristic flow. Thresholds are estimated based on the second-order main flows, periodic flows from the curve of flow durations, analysis of the distribution of annual minima or conventional flows, adapted to specific tasks of water management and environmental development. In this research approach, the low-flow is the period in which the flows are lower than the threshold level (Yevjevich 1967, Ozga-Zielińska 1990, Hisdal et al. 2004). Accordingly, the basic parameter of the identified phenomenon is the streamflow deficit volume in the period when it is lower than the threshold level, and the duration of the low-flow episode (see: Fig. 1).

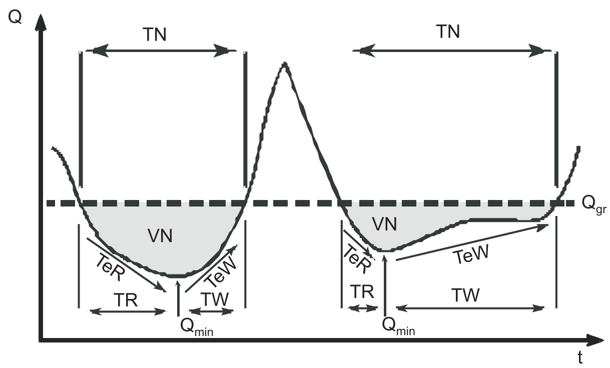

Fig. 1. Parameters of low-flow episode and dynamics of its progression
Q_{gr} – threshold level, VN – low-flow volume, TN – low-flow duration, $Q_{\min}$ – minimal discharge during low-flow episode, TR – low-flow discharge recession time, TW – low-flow discharge rise time, TeR – low-flow discharge recession rate, TeW – low-flow discharge rise rate

RESEARCH MATERIAL

The research covered the catchment area of the upper Warta river, enclosed with a water gauge in Sieradz (see: Fig. 2). The analyses were based on hydrometric material from 12 gauge stations, supervised by IMGW-PIB. The input database consisted of series of daily discharges from the period of 1971–2000. The studied multi-year period was characterized by high dynamics of hydro-meteorological conditions. At the beginning of the 1990s, long-lasting and severe low-flows appeared, whereas the turn of the 1970s and 1980s, and then the second half of the 90s saw many significant floods.

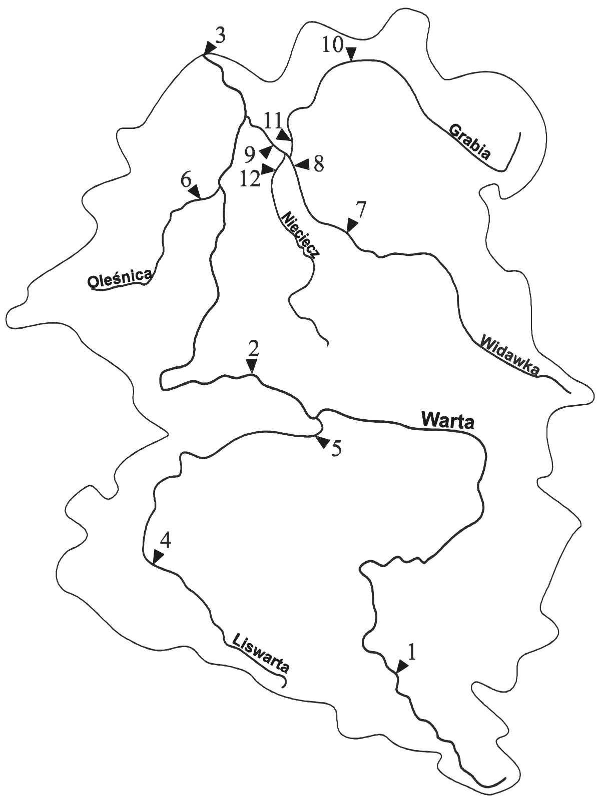

Fig. 2. Study area
River-gauging station: 1 – Warta-Poraj, 2 – Warta-Działoszyn, 3 – Warta-Sieradz, 4 – Liswarta-Niwki, 5 – Liswarta-Kule, 6 – Oleśnica-Niechmirów, 7 – Widawka-Szczerców, 8 – Widawka-Rogóźno, 9 – Widawka-Podgórze, 10 – Grabia-Łask, 11 – Grabia-Grabno, 12 – Nieciecz-Widawa

The southern part of the studied catchment is typified by the existence of capacious underground water reservoirs in well-fissured and karstified rocks, mainly in limestones and dolomites. This results in a low rate of renewal of groundwater resources in the active exchange zone and a slow recession of low flows (Jokiel 1994, Tomaszewski 2007). The northern part of the basin is characterized by much worse retention and a faster rate of groundwater exchange (Jokiel 2004, Tomaszewski 2012). In the eastern part of the catchment (that is, the Widawka river catchment), there is a very strong anthropogenic pressure connected with the activity of "Bełchatów" Open Cast Mine (Jokiel and Maksymiuk 1988). In terms of the impact of water management on low flows, there is a equalisation of minimum flows and the reduction of streamflow deficits in catchments, where the river beds are sealed, as they discharge main waters outside the cone of depression (Tomaszewski 2014). In the unsealed watercourses, placed within the cone of depression, the low-flows are gradually becoming deeper, until periodic, followed by the complete disappearance of streamflow.

STUDY METHOD

In the present study, it was necessary to make an assumption that the occurrence of river low-flows testifies to the occurrence of hydrological drought, while the selected characteristics of the identified low-flow episodes will be the estimators of their corresponding drought characteristics. With reference to the threshold definition of the low-flow phenomenon, a threshold flow was assumed at the level of the 70th percentile, derived from the flow duration curve ($Q_{70\%}$). Only those low-flows, during which the flow was below the threshold level for at least 7 days were subject to identification on a time scale. In terms of separating individual events, it was arbitrarily assumed that the low-flows separated by an interruption lasting no longer than 3 days should be treated as inherently homogeneous events, combining their duration and volume. Based on the above criteria, the identification of the low-flows in the tested group of water-gauge cross-sections was made, and their basic parameters were estimated: duration (TN) and streamflow deficit volume (VN) – see: Figure 1.

The calculated drought streamflow deficit volumes were transformed into a relative deficit (*DWN*), therefore it was possible to compare the results obtained for catchments with different area sizes (Tomaszewski 2012). The presented characteristic is calculated according to the formula:

$$DWN = \frac{V_n}{V_{\max}} \cdot 100\% \qquad (1)$$

where:
DWN – relative drought streamflow deficit, %,
V_n – drought streamflow deficit volume, m^3,
V_{max} – maximum possible streamflow deficit volume during investigated period, i.e. when discharge value equals 0 [m^3].

The above characteristic valorises not only the intensity of the deficit phenomenon, but it also indicates the degree of depletion of the catchment resources, which remain in a hydraulic connection with the low flow. It is worth noting that with the index value of 100% discharge in the riverbed should no longer occur (see: Fig. 3). This measure can therefore be applied as an estimate of the severity of hydrological drought. Furthermore, it facilitates 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 only on observations coming from a given measurement cross-section.

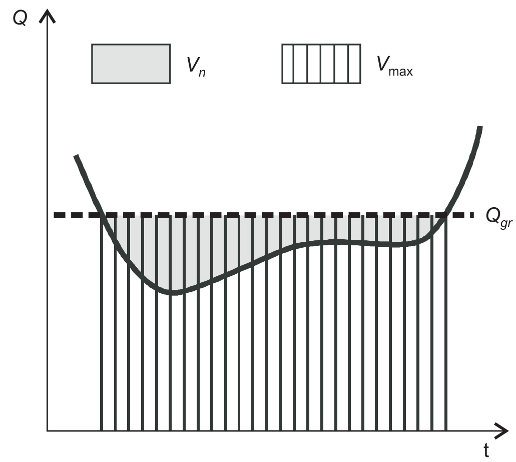

Fig. 3. Graphical illustration of relative drought streamflow deficit estimation
V_n – drought streamflow deficit volume (m^3), V_{max} – maximum possible streamflow deficit volume during the investigated period, i.e. when discharge value equals 0 (m^3)

The dynamics of low-flow episodes progression was assessed based on the low-flow discharge recession rate (Tomaszewski 2012). In order to maintain the comparability of the results obtained, the measure is given in the form of a daily decrease gradient of a specific flow (see: Fig. 1):

$$TeR = \frac{q_{gr} - q_{\min}}{TR} \quad (2)$$

where:
TeR – low-flow discharge recession rate, $dm^3 \cdot s^{-1} \cdot km^{-2} \cdot d^{-1}$,
q_{gr} – threshold level, $dm^3 \cdot s^{-1} \cdot km^{-2}$,
$q_{\min}$ – minimal discharge during low-flow episode, $dm^3 \cdot s^{-1} \cdot km^{-2}$,
TR – low-flow discharge recession time, days.

The dynamics of receding of the low-flow episode was estimated based on the low-flow discharge rise rate:

$$TeW = \frac{q_{gr} - q_{\min}}{TW} \quad (3)$$

where:
TeW – low-flow discharge rise rate, $dm^3 \cdot s^{-1} \cdot km^{-2} \cdot d^{-1}$,
q_{gr} – threshold level, $dm^3 \cdot s^{-1} \cdot km^{-2}$,
$q_{\min}$ – minimal discharge during low-flow episode, $dm^3 \cdot s^{-1} \cdot km^{-2}$,
TW – low-flow discharge rise time, days.

Within the time structure of the development of the low-flow episode, the abscissus of minimum discharge position was assessed (Tomaszewski 2012):

$$WP = \frac{TR}{TN} \quad (4)$$

where:
WP – index of low-flow minimum discharge position,
TR – time of recession, days,
TN – low-flow duration, days.

The presented characteristic can take values from the range between 0 and 1. The characteristic value is 0.5, which means that the minimum discharge (Q_{min}) is located exactly in the middle of the low-flow period. Values lower than 0.5 indicate shifting of the extreme closer to the beginning of the low-flow, and values greater than 0.5 are pointing to its occurrence in the second half of the episode.

The last of the used characteristics, allowing for a comprehensive assessment of the dynamics of the low-flow episode, was the low-flow stability index (Tomaszewski 2012):

$$WSN = \frac{Q_{gr} - Q_{sr}}{Q_{gr} - Q_{\min}} \quad (5)$$

where:
WSN – low-flow stability index,
Q_{gr} – threshold level, $m^3 \cdot s^{-1}$,
$Q_{śr}$ – medium discharge during low-flow episode, $m^3 \cdot s^{-1}$,
$Q_{\min}$ – minimal discharge during low-flow episode, $m^3 \cdot s^{-1}$.

The obtained results may vary within the range between 0 and 1. Values close to 1 are the result of a rapid decrease of the discharge at the beginning of the low-flow episode, and its maintenance at a constant, minimum level until its completion; theoretically, the value of 1 means that the low-flow stays the same from the beginning to the end of the episode. The decrease in the value of WSN means the increasing variability of discharge during the low-flow episode, and the increase in the significance of discharges appeared in the minor phase of the low-flow.

By adopting the river low-flow as the estimate of the hydrological drought development, the following assumptions were made for the purpose of the present work:

- the occurrence of river low-flow reflects the presence of hydrological drought in the catchment;
- hydrological drought is significant from a spatial point of view, if the low-flows were recorded in at least 50% of the studied water-gauging stations;
- the beginning of the low-flow in the river means the beginning of the hydrological drought, whereas the end of the low-flow is associated with the end of drought.

In accordance with the adopted assumptions, for the hydrological drought to be spatially significant, at least 6 gauging stations should record low-flows. In this way, 23 hydrological droughts were identified within the studied catchment area in the period of 1971–2000 (see: Table 1). Among these episodes, simple and complex hydrological droughts were observed (see: Fig. 4). In the case of the latter, it was assumed that the subsequent developmental stages belong to the same hydrological drought, if the intervals between successive low-flows did not exceed 30 days.

Table 1. Characteristics of hydrological droughts in the Warta river catchment up to Sieradz (1971–2000)

No.	Year	Season	TS	WZS	WSS	TeRS	TeWS	WPS	WSNS
			days	%		$dm^3 \cdot s^{-1} \cdot km^{-2} \cdot d^{-1}$			
1	1971–1972	VII – XI	132	72	18	0.190	0.170	0.480	0.610
2	1972	V–X	116	63	18	0.370	0.310	0.520	0.630
3	1973	XII–I	48	89	15	0.300	0.180	0.390	0.580
4	1973–1974	IV–XII	244	89	16	0.285	0.195	0.455	0.580
5	1974	III–VII	122	87	12	0.145	0.360	0.580	0.565
6	1975	IV–X	175	70	14	0.130	0.200	0.520	0.570
7	1976	V–X	164	94	14	0.160	0.150	0.520	0.510
8	1978	V–IX	103	100	11	0.140	0.160	0.433	0.633
9	1979–1980	V–I	244	89	9	0.115	0.110	0.570	0.515
10	1982–1983	VII–XII	137	70	9	0.100	0.060	0.360	0.530
11	1983–1985	VI–IV	599	97	13	0.110	0.170	0.573	0.573
12	1986	II–X	250	96	13	0.313	0.290	0.423	0.583
13	1987	VI – X	112	100	11	0.150	0.150	0.460	0.570
14	1988–1989	IV–XII	230	100	14	0.116	0.271	0.617	0.602
15	1989–1994	III–XII	1731	100	21	0.169	0.181	0.500	0.601
16	1994–1995	VI–XI	169	100	23	0.087	0.080	0.471	0.519
17	1995	V–III	322	100	19	0.113	0.183	0.589	0.580
18	1996	IV–IX	137	80	15	0.137	0.269	0.541	0.594
19	1997	XII–II	45	91	15	0.177	0.188	0.505	0.522
20	1997	IV–VII	78	96	9	0.177	0.250	0.633	0.555
21	1998	IV–X	154	100	11	0.100	0.102	0.407	0.568
22	1999–2000	VII–XII	135	97	23	0.091	0.117	0.518	0.600
23	2000	IV–VII	100	97	18	0.083	0.107	0.637	0.607

TS – drought duration, WZS – drought range index, WSS – drought severity index, TeRS – low-flow runoff recession rate, TeWS – low-flow runoff rise rate, WPS – index of low-flow minimum discharge position, WSNS – low-flow stability index during drought

The duration of the drought (TS) was determined by the difference between the date of the appearance of the first low-flow and the last day of the last low-flow, including the intervals between the low-flows, if any. Next, the average rate of recession (TeRS) and rate of rise (TeWS) of the low-flow runoff during the hydrological drought was estimated, based on formulas 2 and 3. The average index of low-flow minimum discharge position during drought (WPS) and low-flow stability index during drought (WSNS) were estimated accordingly (using formulas 4 and 5).

In addition to the dynamic characteristics, the range and severity of the hydrological drought were also evaluated. The range index shows what part (that is, what share) of the catchment was covered by the drought in its maximum stage of development:

$$WZS = \frac{\Sigma A_i}{A} \cdot 100\% \qquad (6)$$

where:
WZS – hydrological drought range index, %,
ΣA_i – sum of catchment areas in which the low-flows has occurred, km^2,
A – area of the entire catchment, km^2.

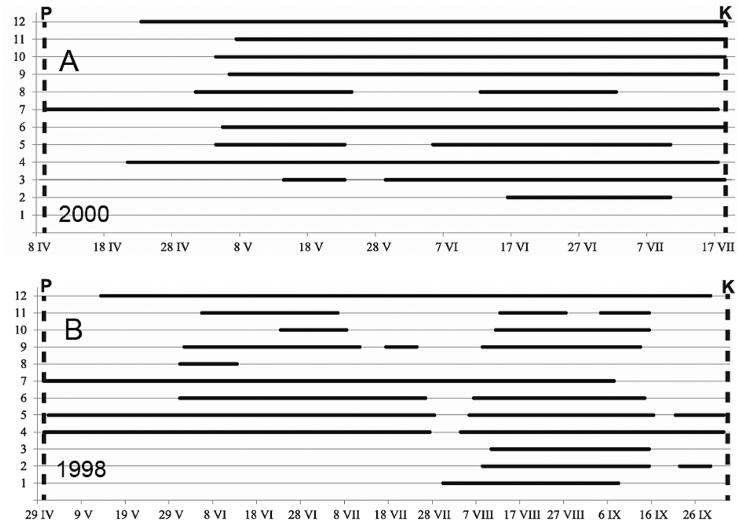

Fig. 4. Examples of the course of simple (A) and compound (B) hydrological drought 1–12 – number of catchment – see Figure 2, P – beginning of hydrological drought, K – end of hydrological drought

The last parameter characterizing the hydrological drought is the drought severity index (*WSS*), which was determined on the basis on the relative drought streamflow deficit for each water-gauging station (according to formula 1), and then substituted in the weighted average, where the catchment area size was the weight:

$$WSS = \frac{\sum_{i=1}^{N}(DWN_i \cdot A_i)}{\sum_{i=1}^{N} A_i} \qquad (7)$$

where:
WSS – hydrological drought severity index, %,
DWN_i – relative drought streamflow deficit in catchment *i*, %,
A_i – area of catchment *i*, km^2,
N – number of catchments on which low-flows have occurred.

THE RANGE AND SEVERITY OF HYDROLOGICAL DROUGHT

The average duration of hydrological drought in the Warta river catchment in the studied multi-year period was 241 days. The longest drought lasted almost 5 years, and it included the period of 1989-1994 (see: Fig. 5). The aforementioned drought event was the result of a series of dry years (Stachý 2011), which caused a series of severe low-flows throughout central Poland (Tomaszewski 2012) and other regions of the country. One more serious hydrological drought occurred in 1983–1985, and it lasted for 599 days. The shortest observed hydrological drought lasted for 1.5 months, and dry periods not exceeding one quarter constituted one-third of the identified episodes.

The average range of hydrological drought in the studied catchment amounted to 90%, which means that droughts mostly covered almost the entire Warta river catchment. This parameter in the studied multi-year period ranged from 63 to 100% (see: Table 1). The smallest range was recorded for the drought of the year 1972 (see: Fig. 5), which covered the upper and lower Warta river and the Widawka river catchments. Droughts with maximum range dominated in the 1990s. It is worth noting that the shorter drought episodes occurred mainly in the warm half-year, when the precipitation deficits was strongly enhanced by evapotranspiration with a well-developed vegetation cover.

The degree of hydrological drought severity in the studied catchment ranged from 9 to 23% (see: Ta-

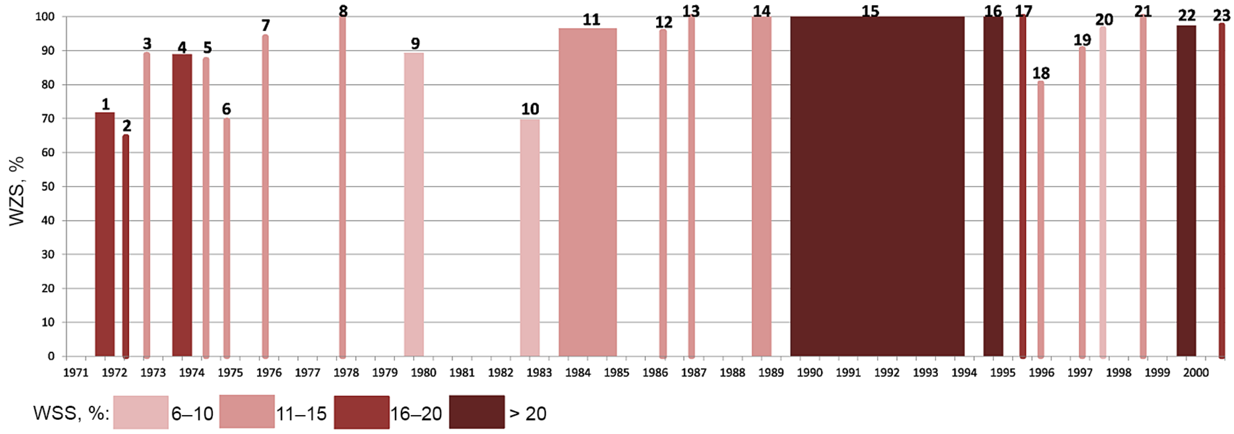

Fig. 5. Range and severity level of hydrological drought events in the upper Warta river catchment (1971–2000)
WZS – drought range index, WSS – drought severity index, for numbers of drought episodes, see: Table 1

ble 1), whereas the average value of this characteristic was 15%. The highest severity (23%) was recorded for droughts in the years 1994–1995 and 1999–2000 (see: Fig. 5). In the first case, the drought occurred over the entire catchment area, in the second case, it also covered a large range (97%), and did not occur only in the upper part of the catchment (Poraj).

In the multi-year course of hydrological droughts in the upper Warta river catchment, two characteristic periods can be observed (see: Fig. 5). In the 1970s, relatively short droughts dominated, with a varying range and degree of severity, occurring both in the cool and warm half-years. In the mid-1980s, the first longer drought appeared (lasting for 599 days), after which an increase in the drought range was visible, up to the peak in the period of 1989–1994. It can be assumed that the depletion of resources of the active exchange zone during this almost 5-year drought was so large that subsequent droughts appearing in the second half of the 1990s were characterized by a much greater range and degree of severity than those at the beginning of the studied multi-year period. It is also worth noting that there is no clear relationship between the length of the drought and its range or degree of severity (see: Fig. 6). Drought events with a greater or lesser degree of severity occur in the entire range of the recorded droughts. It can only be noted that very long droughts always covered the entire studied catchment area. However, already slightly shorter episodes do not show a clear correlation with drought range. The above observations lead to the conclusion that the development of hydrological drought in the studied catchment is not determined solely or mainly by hydro-meteorological conditions. An important role in this process is played by hydrogeological properties and the groundwater regime of the active exchange zone, the state of underground retention prior to drought, as well as water management activities, which modify the distribution of low flows – such as forced infiltration associated with the mine's cone of

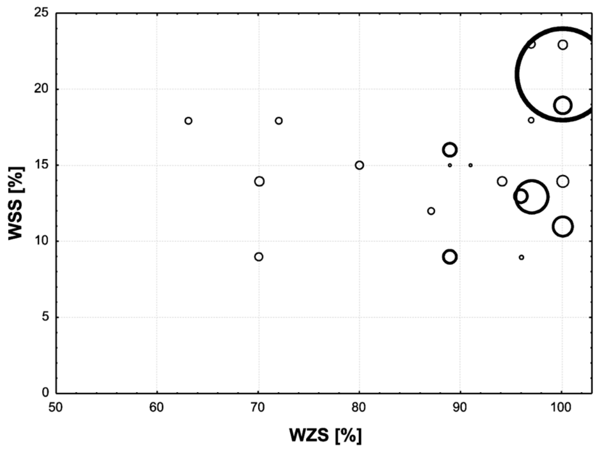

Fig. 6. Relationship between drought duration (TS), its range (WZS) and severity level (WSS) in the upper Warta river catchment (1971–2000)
Diameter of a circle is proportional to the length of hydrological drought length (TS)

depression (at Nieciecz), main water discharges (at Widawka), and the water management on the dam reservoir (at Poraj).

LOW-FLOW DYNAMICS DURING HYDROLOGICAL DROUGHT

The average rise and recession rate of low flows resulting from the analysed hydrological droughts within the catchment amounted respectively 0.16 and 0.19 $dm^3 \cdot s^{-1} \cdot km^{-2} \cdot d^{-1}$. The highest dynamics of progression can be observed in the case of drought events in the 1970s, which had a relatively short duration, and were characterized by low range indicators (see: Fig. 7, Table 1). During this period, the Widawka river catchment had the greatest impact on the dynamics of the drought's development. This was related to the commencement of water drainage works at the mine, during which the cone of depression was developing dynamically, resulting in high dynamics of main water discharges to the Widawka river system, combined with naturally occurring periods with restricted alimentation, in turn causing high dynamics of recession and rise of low-flows. The high recession rate of the low flow was also visible during the drought covering almost three quarters of the year 1986. Among the hydrological droughts of the 1990s, episodes from 1996 and 1997 were highly dynamic (see: Table 1). It is worth noting that this dynamics refers to the phase of low-flow rise, and it includes the summer period. It is impossible not to associate this with high flood waves occured in the whole area of Poland at that time, and interrupted summer low-flows; among them was the famous "millennium flood" of the year 1997. The described relationship can be transferred to the majority of the identified hydrological drought episodes, ending or having the main development phase in the summer season, when the rate of drought recession is always slightly higher than the rate of its progression.

The average index of the low-flow minimum discharge position during the investigated drought events amounted to 0.51, which means that the "model" low-flow reaches its minimum almost exactly in the middle

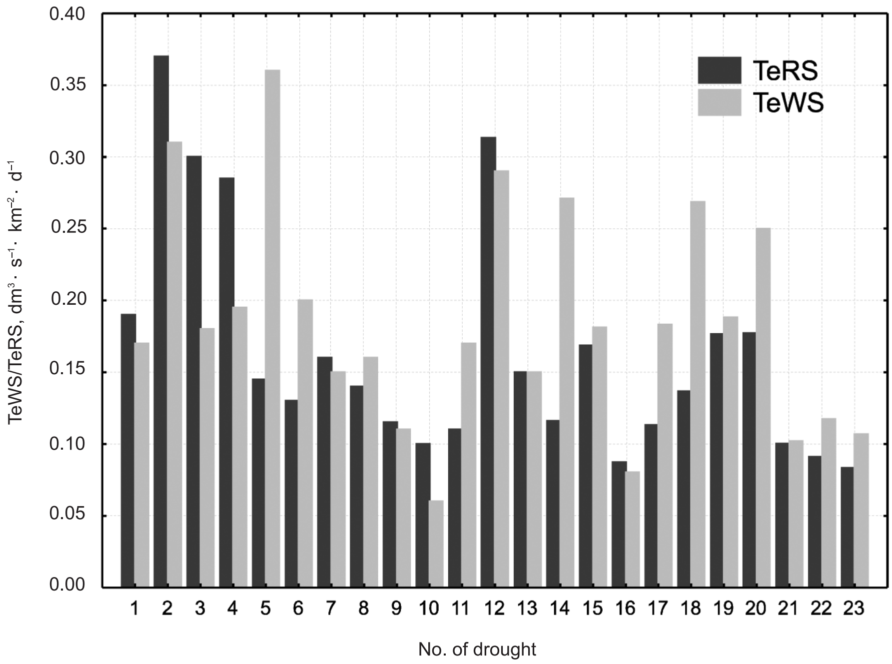

Fig. 7. Distribution of low-flow discharge recession (TeRS) and rise (TeWS) rate in subsequent hydrological droughts
No of drought, see: Table 1

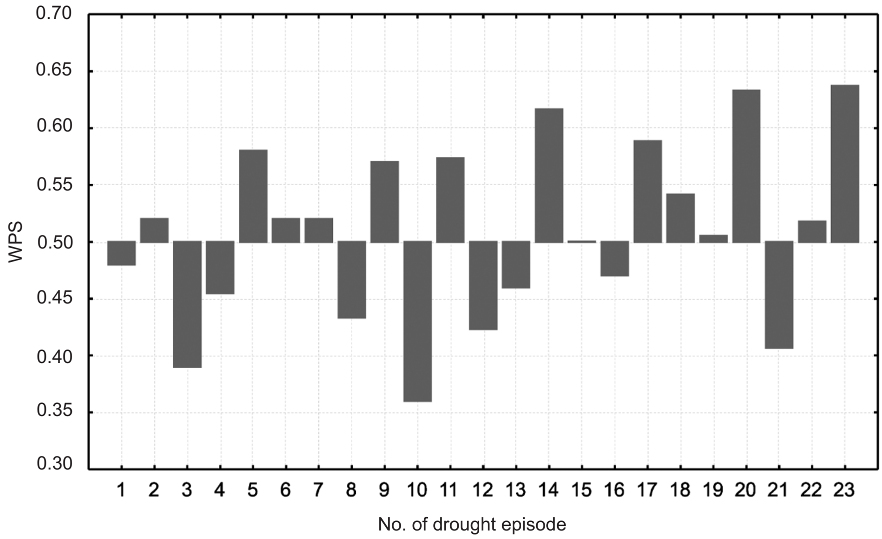

Fig. 8. Distribution of the index of low-flow minimum discharge position during drought in subsequent hydrological droughts
For numbers of drought episodes, see: Table 1

of its duration (see: Table 1). However, temporal analysis of the course of this characteristic shows some variability (see: Fig. 8). Generally speaking, the WPS index for subsequent drought events remains in the range of 0.45–0.55. However, every 2 to 3 droughts, the value of this characteristic goes beyond this range. It should be noted that relatively short drought episodes with the duration of 48 to 250 days (1973, 1978, 1982, 1986, 1998) are characterized by low WPS values, which is the result of a relatively rapid development of drought in the catchment area, and its gradual disappearance. In relation to droughts characterized by high WPS values, it should be stated that the impact of factors determining the occurrence of the minimum flow in the second half of the low-flow event is more complex, since no correlation has been observed with any of the defined characteristics. It is worth emphasizing, however, that with the lapse of time, in the analysed multi-year period, the phase of its development is gradually lengthening in the structure of the hydrological drought, whereas the phase of recession is shortening.

The calculated low-flow stability indicators show slight differentiation between individual droughts, as their values oscillate within the range between 0.51 and 0.63 (see: Table 1). This shows the relative stability of the low flow regime, related to the hydrogeological features of the active exchange zone of the catchment. However, it is worth noting the occurrence of gradual increases and decreases of the WSNS from drought to drought (see: Fig. 9). This pattern with some exceptions, may attests to certain inertia which results from the fact that the degree of filling the groundwater reservoirs, as a result of the degree of severity of the previous drought event and

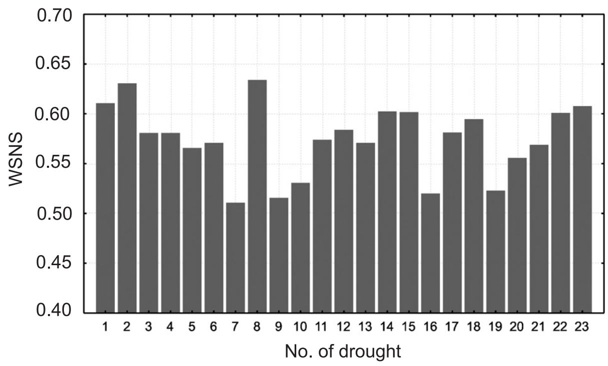

Fig. 9. Distribution of low-flow stability index in subsequent hydrological droughts
For numbers of drought episodes, see: Table 1

the efficiency of restoring resources between the droughts significantly affects the variability of supply and the dynamics of retention in the next hydrological drought event.

CONCLUSIONS

The research that have been carried out indicate that the application of low-flows as an indicator of the hydrological drought development brings promising results. The adopted identification and separation criteria facilitated the unambiguous isolation of simple and compound hydrological droughts in the upper Warta river catchment in the period of 1971–1990. The transformation of characteristics related to the duration and relative deficit of low-flows and their share in the overall number of water gauges allowed to valorise hydrological drought in terms of its severity and range, and to indicate periods of varying specificity of the studied phenomenon development. The characteristics, being the estimators of the rise and recession rate of hydrological drought, not only made it possible to identify a group of factors determining the development of hydrological drought, but they also showed weak relationships with other studied measures, which proves the complex genesis of the observed processes, requiring further study.

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WYBRANE CHARAKTERYSTYKI ROZWOJU SUSZY HYDROLOGICZNEJ W ZLEWNI GÓRNEJ WARTY

ABSTRAKT

W opracowaniu dokonano identyfikacji susz hydrologicznych, przyjmując założenie, że niżówka rzeczna będąca przejawem suszy jest jednocześnie dobrym estymatorem jej rozwoju. Badania przeprowadzono w zlewni górnej Warty, dla której dysponowano dobowymi seriami przepływów dla 12 posterunków wodowskazowych z okresu 1971–2000. Niżówki rzeczne zidentyfikowano na podstawie stałego w wieloleciu przepływu granicznego, odpowiadającego 70. percentylowi z krzywej czasów trwania przepływu wraz z wyższymi ($Q_{70\%}$). Dla zidentyfikowanych niżówek oszacowano parametry związane z ich czasem trwania, niedoborem odpływu oraz dynamiką przepływu podczas epizodu. Przyjęte kryteria identyfikacyjne i separacyjne pozwoliły na jednoznaczne wyodrębnienie prostych i złożonych susz hydrologicznych. Transformacja charakterystyk związanych z czasem trwania i deficytem względnym niżówek oraz ich udziałem w ogólnej liczbie wodowskazów umożliwiła waloryzację suszy hydrologicznej w zakresie stopnia jej surowości oraz zasięgu. Charakterystyki będące estymatorami tempa rozwoju i zaniku suszy hydrologicznej pozwoliły na określenie czynników determinujących badane zjawisko oraz jego zmienność czasową.

Słowa kluczowe: niżówka rzeczna, niedobór odpływu niżówkowego, stopień surowości suszy, dynamika przepływów niżówkowych