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ORIGINAL PAPER Accepted:

SPATIAL VARIABILITY OF LOW-FLOWS IN THE UPPER WARTA RIVER CATCHMENT

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ABSTRACT

Low-flows are an important component of the river regime. Their identification advances our knowledge about the formation of water resources in drought conditions. The analyses that we have carried out aimed to indicate the spatial structure of these flows. Our study area was the Warta River catchment up to the water-gauge at Sieradz. The input research material consisted of a sequence of daily discharge data for 12 gauging stations located in this catchment, in the period of 1971-2000, made available by IMGW-PIB. At the first stage, periodic flows based on flow time-duration curve and annual minimum flows were determined. Their values have been converted into specific flows, which facilitated the conduct of comparative analyses. On the basis of the obtained results, the spatial variability of low-flows in studied catchment was evaluated. The annual number of days with low-flows was identified for all gauge sections. The dynamics and distribution of low flow appearing in the multiannual period were evaluated. The analyses we have carried out made it possible to identify the factors, which determine the structure of low-flows. Research results have been illustrated with relevant maps and graphs.

Keywords: characteristic flows, spatial variability of flow, hydrological drought

INTRODUCTION

Low-flows are one of the most important constituents of the river regime (Bartnik, Jokiel 2005). Their proper identification and recognition provides information on the nature of outflow from the catchment, and also gives the opportunity to assess the variability thereof (Kaznowska et al. 2015). The size of the outflow and its structure depend on the conditions of the geographical environment. The climatic conditions, the terrain and the geological structure play the most important role here, as they determine many hydrological processes, including surface runoff or infiltration. Other important factors include land use and human activity (Brykała 2009, Michalczyk 2017). In the Polish literature on the subject, we find numerous studies on the temporal and spatial variation of outflows in different regions of the country (e.g. Jokiel 1994, 2004, Brykała 2009, Pociask-Karteczka et al. 2010, Bartczak et al. 2014, Franczak et al. 2015). An important role in the structure of river outflow is played by the above-mentioned extreme phenomena, that is, the low-flows. They are a manifestation of the developing hydrological drought, which is why their detailed recognition and exploration of their spatial variability creates the possibility of undertaking rational steps aimed at minimizing the negative effects of this phenomenon (Tomaszewski 2017). The main objective of the present study is to assess the spatial variability of low-flows in the upper Warta River catchment, which experiences the occurrence of deep low-flows, and which is characterized by diverse physiographic and hydrological conditions.

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STUDIED MATERIAL AND AREA

The upper Warta River catchment is located in the Warta sub-region including both upland and lowland terrain (Paczyński, Sadurski 2007). The upper part of the catchment is characterized by groundwater (karst and fissure-karst) with the highest abundance in the entire examined area. They occur mainly in Cretaceous limestone, Jurassic limestone, and Triassic and Devonian dolomites (Mikulski 1963, Richling 2006). The groundwater supply coefficient reaches 80% in this part of the catchment, the retention capacity of the hydrologically active zone is very high, whereas the susceptibility to groundwater recovery is low (Jokiel 1994, 2004). The greater part of the upper catchment of the Warta River consists of the waters from the degraded uplands, characteristic of the Central Poland Lowlands. In the central part of the basin (near Działoszyn) there are waters exchanged between the marl crevices and the ground (sunken marlstone) (Richling 2006). This area is characterized by an underground supply coefficient of 50–60%, while the general retention capacity varies from medium to high, and susceptibility to water recovery is between average and low. The lowest coefficient of groundwater supply (40–50%) and low retention describe the lower part of the catchment area under examination, whereas the susceptibility to groundwater recovery is average in this case (Jokiel 1994). Water regime of the investigated section of the Warta River was recognized by Dynowska (1994) as a nival regime, moderately formed. The upper Warta River catchment is characterized by higher values of the average unit runoff (5.1–8.1 $dm^3s^{-1}km^{-2}$) and underground runoff (4.6–5.0 $dm^3s^{-1}km^{-2}$) in relation to central Poland and the whole country (Jokiel 2004). In the studied catchment, various aspects of water management can be found. Those having the most impact on the runoff include drainage of the deposit in the KWB "Bełchatów" coalmine (in the eastern part of the catchment), and water management activities carried out on the Poraj reservoir (in the southern part of the catchment). The draining of the deposit and the operation of the reservoir generate changes in the water environment. Hydrodynamic changes associated with drainage of water in the excavation field lead to the formation of a depression cone, while the functioning of the reservoir provides a minimum acceptable flow below the dam (0.55 m^3s^{-1}) and reduces the maximum flows, which is associated with the flood control function (Motyka et al. 2007, Szewczyk 2007, Wachowiak et al. 2011). In the Poraj water-gauge, located below the dam, a reduction of characteristic and average flows is also observed. This may be caused by infiltration and the escape of the limestone waters through rock layers under the bottom of the reservoir, associated with the presence of hydrogeological windows in fault zones or mining activities (exploitation and drainage of deposits in the Poraj region) causing the formation of depression cones (Jaguś, Rzętała 2000).

The study of spatial variability of low-flows was based on sequences of data on daily flows from the thirty-year period between 1971–2000, observed at 12 water gauging stations in the upper Warta River catchment, made available by IMGW–PIB. Both the number and the placement of water gauging stations made it possible to study the spatial variability of low-flows and the conditions determining that variability. The investigated catchments vary in their sizes. The smallest area is 222 km^2, while the largest one exceeds 8000 km^2 (see: Table 1).

Low-flows are those flows that persist during periods of limited river supply. Starting from the definition of low-flows, based on the constant threshold flow method, all daily flows that remain below a certain threshold value will be included in the category of low-flows. In the subject literature, there are many methods for determining the threshold flow ordinate (Tomaszewski 2012). This value is most often assumed as the main flows of the 2nd degree, or ordinates derived from the curve of the sum of time-durations (along with the higher ones) (Kaznowska 2006, Tokarczyk 2008, Tomaszewski 2012). Conventional characteristic flows are also applied, such as minimum acceptable flow, minimum navigational flow, and other parameters guaranteeing correct operation of hydrotechnical devices (Ozga-Zielińska, Brzeziński 1997, Byczkowski 1999, Tomaszewski 2012). In the present study, the threshold values were determined based on periodic flows. The threshold for low-flows in the mildly developed hydrological drought was assumed to be the 70th percentile from the curve of the total time-duration of flows along with the higher ones, whereas for the more severe hydrological drought, 95th percentile was assumed. In the subject literature, the latter is considered to be the ordinate, below which the deep low-flow phase occurs (Dębski 1970, Strzebońska-Ratomska 1994, Tomaszewski 2012). The resulting flow ordinates were converted into unit outflows – $q_{70\%}$ and $q_{95\%}$ respectively (see: Table 1). In addition, durations of low-flows were identified, counting the days in which the flow remained below the threshold value. The annual and multi-annual outflow minima were also determined (Nq/NNq) and their spatial variability was examined. For the annual values of estimated outflows, coefficients of variability were calculated in order to check their dynamics in the studied 30-year period (Tomalski, Tomaszewski 2015):

$$cv\,x = \frac{os\,x}{śr\,x} \quad (1)$$

where:
cv x – coefficient of variation,
os x – standard deviation of the variable x,
śr x – arithmetic mean of the variable x.

LOW-FLOWS IN MILDLY DEVELOPED HYDROLOGICAL DROUGHT

The periodic outflows of $q_{70\%}$ demonstrate considerable variation in the studied catchment area (see: Figure 1). Their lowest values are found in small lowland catchments (Nieciecz and Oleśnica), as a result of limited hydraulic contact with the drained aquifers (Jokiel 1987, Tomaszewski 2012). Furthermore, Nieciecz is within the reach of the depression cone, which reduces the size of the river runoff in this particular catchment (Wachowiak et al. 2011). Low $q_{70\%}$ outflows from the range of 2-3 $dm^3s^{-1}km^{-2}$ are also typical for other small catchments - Grabia and Liswarta up to Kule. They also concern the Warta River in Poraj, which may be due to the impact of the Upper Silesian mines leading to the lowering of the groundwater table due to the formation of local and regional depression cones (Jaguś, Rzętała 2000). Higher values of the tested outflow ordinate occur in the Warta catchment up to Sieradz, which possess significant water resources, and the Liswarta catchment up to Niwki, which is located in the upland part of

Table 1. Specific low-flows in upper Warta river catchment (1971–2000)

No.	River	Water gauge	*A* [km^2]	$q_{70\%}$ [$dm^3s^{-1}km^2$]	$q_{95\%}$ [$dm^3s^{-1}km^2$]	NNq [$dm^3s^{-1}km^2$]	R^2	a
1	Warta	Poraj	535	2.95	1.89	0.63	–	–
2	Warta	Działoszyn	4101	4.19	2.73	1.90	0.31	–0.043
3	Warta	Sieradz	8185	3.91	2.69	1.83	0.16	–0.027
4	Liswarta	Niwki	222	3.96	2.34	0.50	0.46	–0.065
5	Liswarta	Kule	1545	2.97	1.62	0.71	0.41	–0.063
6	Oleśnica	Niechmirów	584	1.64	0.80	0.33	–	–
7	Widawka	Szczerców	719	6.84	4.01	2.25	–	–
8	Widawka	Rogóźno	1182	5.41	3.72	2.01	–	–
9	Widawka	Podgórze	2377	3.87	2.51	1.08	–	–
10	Grabia	Łask	470	2.91	1.49	0.49	0.17	–0.023
11	Grabia	Grabno	816	2.49	1.42	0.77	0.16	–0.032
12	Nieciecz	Widawa	259	1.78	0.39	0.01	0.27	–0.041

A – size of catchment area, $q_{70\%}$ –70-percentile periodic flow, $q_{95\%}$ – 95.–percentile periodic flow, NNq – the lowest low flow, R^2 – determination coefficient of statistically significant (α=0.01) linear trend of annual Nq low flow, a – slope coefficient of statistically significant (α = 0.01) linear trend of annual Nq low flow

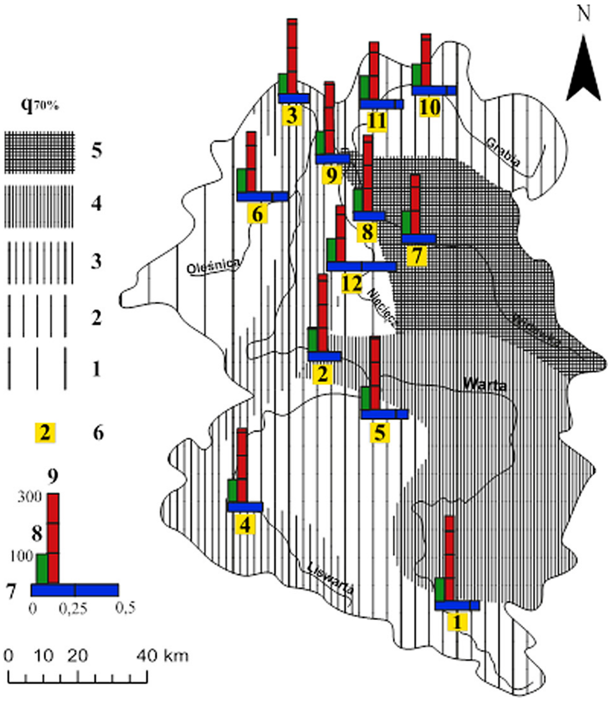

Fig. 1. Spatial variability of periodic flow $q_{70\%}$ and annual number of days with low-flows ($T_{70\%}$) in the upper Warta River catchment (1971–2000)
Multiannual periodic flow $q_{70\%}$ [$dm^3 \cdot s^{-1} \cdot km^{-2}$]: 1 – 1-2, 2 – 2-3 , 3 – 3-4, 4 – 4-5 , 5 – >5, 6 – number of catchment, see tab. 1, 7 – variation coefficient of periodic flow $q_{70\%}$ ($cv(q_{70\%})$), 8 – annual average number of days with low-flows ($śrT_{70\%}$), 9 – annual maximum number of days with low-flows ($maxT_{70\%}$)

the studied area and has rich fissure-layer marlstone karst waters with slow recovery rates (Jokiel 1994, Richling 2006). Warta up to Działoszyn and upper Liswarta both have rich aquifers, with $q_{70\%}$ exceeding 4 $dm^3s^{-1}km^{-2}$ (Paczyński, Sadurski 2007). The largest values of periodic outflows ($q_{70\%}$) are encountered in Widawka, a catchment burdened with strong anthropogenic pressure. As a result of the drainage of the KWB "Bełchatów" coalmine, Widawka receives underground discharges, which makes the flow of the river much larger than the natural one.

The coefficients of variation of $q_{70\%}$ annual periodic outflows in the Upper Warta catchment are small, and they range from 0.22 in Sieradz to 0.5 in Widawa. The greatest long-term diversity is shown by small lowland catchments – Nieciecz and Oleśnica, susceptible to falling into low-flows, as a result of low water resources of the hydrologically active zone (Tomaszewski 2012). These basins are characterized by a high recession rate of groundwater resources of the active exchange zone in drought conditions, as well as a high rate of flow increase due to rain or thaw impulse. Additionally, the Nieciecz catchment is covered by a depression cone, which significantly affects $q_{70\%}$ and their variability. Dehydration in this area began in 1975, therefore the size of $q_{70\%}$ in this catchment differs in the 30-year study depending on the economic activity and extent of the depression cone (Motyka et al. 2007). In the Oleśnica catchment, we also encounter the manifestations of water management activities (water melioration, water discharge from sewage treatment plants), which can affect the increase in the value of cv ($q_{70\%}$). High variability also applies to Warta River in Poraj, which is related to the human activity above the dam.

The average annual number of days with low flow $T_{70\%}$ in the upper Warta River catchment in the years 1971-2000 is 102, and it ranges from 96 in Sieradz to 108 in Działoszyn (see: Figure 1). The spatial variability of this characteristic is small. The prolongation of low-flows in the upland part of the Warta River catchment may be affected by low susceptibility to groundwater recovery. High values of $maxT_{70\%}$ are also observed here. This characteristic shows greater variation in the studied catchment area than the average annual number of days when this phenomenon occurs. The average value is 292 days. The maximum long-term low-flows persisted in the Warta catchment up to Poraj, lasting for 365 days in 1991. The prolonging of these flows is influenced by the economic activity conducted on the reservoir, and meeting the needs of the users. High values of $maxT_{70\%}$ are also found in the lower part of Widawka catchment (Rogóźno and Podgórze). Low-flows in 1990 lasted here for over 300 days, and they were associated with hydrological droughts of the 1990s. Hydro-meteorological conditions in this period had a stronger impact in the lower part of Widawka than the underground water discharges, which indicates a high degree of severity of this drought. The lowest value of $maxT_{70\%}$ was recorded in the Grabia and Nieciecz catchment, whose susceptibility to resource recovery is relatively high compared to the southern part of the catchment. In addition, there are many fish breeding ponds in the Grabia catchment that regulate the hydrographic conditions in this area. When analysing the annual distribution of $T_{70\%}$, we notice that in some years the number of days with low flow is 0 (see: Figure 2). This is connected with significant flood periods and sequences of wet years, which appeared at the beginning and at the end of the studied multi-year period, as well as at the turn of the 1970s and 1980s.

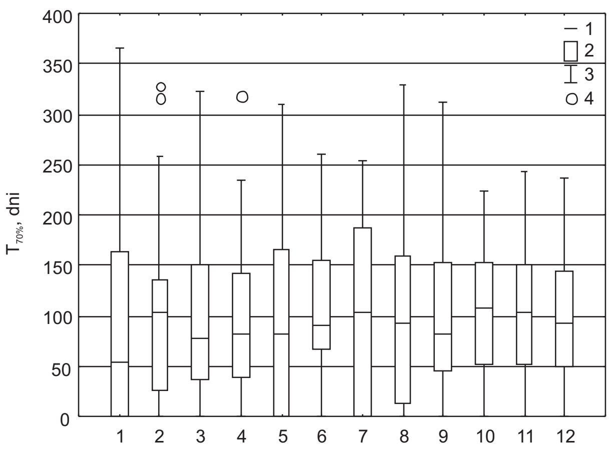

Fig. 2. Distribution of annual number of days with low-flows ($T_{70\%}$) in the upper Warta river catchment (1971–2000)
$T_{70\%}$ – annual number of days with low-flows, 1 – median, 2 – range between first and third quartile, 3 – range limited by 1 quartile deviation, 4 – outliers under 1.5 quartile deviation, 1,2,…12 – number of catchment, see tab. 1

The highest values of $T_{70\%}$ relate to the early 1990s, when long-lasting deep low-flows were observed, which is a manifestation of a severe hydrological drought (Tomaszewski 2012). $T_{70\%}$ distributions in the catchments that we have studied are asymmetric and right-sided, and they are the result of a sequence of dry years (at the beginning of 1990s), during which the number of days with low flow was much bigger than in other years. Outliers were observed only in the rich, upland part of the catchment (Działoszyn and Niwki), and they are also associated with the dry season, when resources of the active exchange zone could be depleted, and due to the low susceptibility of these catchments to resource recovery, low-flows lasted for a relatively long time.

LOW-FLOWS DURING SEVERE HYDROLOGICAL DROUGHT

The periodic outflows of $q_{70\%}$, being a manifestation of hydrological drought with a significant degree of severity, also show a clear differentiation (see: Figure 3). Their spatial distribution is close to the representation of variation for $q_{70\%}$. The lowest values of $q_{95\%}$ (below 1 $dm^3s^{-1}km^{-2}$) concern small lowland catchments, such as Nieciecz and Oleśnica, which are characterized by a high rate of recession of groundwater resources from the active exchange zone in drought conditions. The same situation was noted for periodic outflows during a mild drought. In the Nieciecz catchment, periodic outflows $q_{95\%}$ reach an average of 0.39 $dm^3s^{-1}km^{-2}$, which is much less than those observed for $q_{70\%}$ (1.78 $dm^3s^{-1}km^{-2}$). Slightly higher $q_{95\%}$ (1-2 $dm^3s^{-1}km^{-2}$) have been observed on Warta in Poraj, on Liswarta in Niwka, and on Grabia. These catchments also had similar $q_{70\%}$ values, which were slightly higher, namely: 2-3 $dm^3s^{-1}km^{-2}$. The difference in the spatial distribution can be observed in the Warta catchment area up to Działoszyn. It adopts $q_{95\%}$ values from the same range as the Warta river catchment up to Sieradz, and Liswarta river catchment up to Kule (2-3 $dm^3s^{-1}km^{-2}$), which has not been observed in the spatial distribution of $q_{70\%}$ outflows. Despite the significant retention capacity of reservoirs in that area, severe hydrological droughts play an important role in this catchment, due to the low susceptibility to water resources recovery. It can also be observed that $q_{95\%}$ outflows in the lower catchment of Widawka River are smaller than their counterparts in the upper part of that same river, which was not observed for the value of $q_{70\%}$. In Szczerców, above which water discharges from the mine are present, $q_{95\%}$ outflows reach the highest values, namely: above 4 $dm^3s^{-1}km^{-2}$. Progressively with the course of the river, the influence of water management on the outflow is decreasing.

Variability of outflows $q_{95\%}$ is the same as that for $q_{70\%}$. The largest $cv(q_{95\%})$ occur in small catchments, such as Nieciecz (0.67), Grabia (0.39) and Oleśnica (0.37). These catchments are characterized by a greater variability of periodic outflows during a severe hydrological drought than during a mild drought period. The $q_{95\%}$ outflow is associated with the phase of full development of the hydrological drought, during

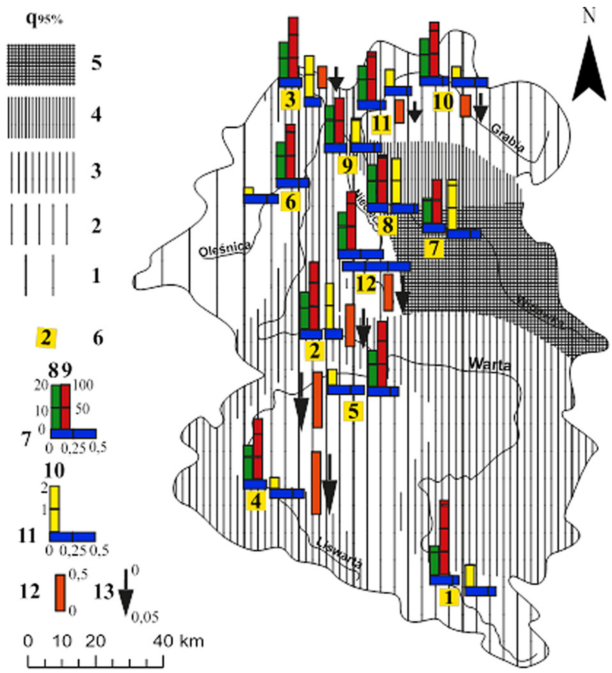

Fig. 3. Spatial variability of periodic flow $q_{95\%}$ and annual number of days with low-flows ($T_{95\%}$) in the upper Warta river catchment (1971–2000)
Multiannual periodic flow $q_{95\%}$ [$dm^3s^{-1}km^{-2}$]: 1 – <1, 2 – 1-2, 3 – 2-3, 4 – 3-4 , 5 - >4, 6 – number of catchment, see tab. 1, 7 – variation coefficient of periodic flow $q_{95\%}$ (cv($q_{95\%}$)), 8 – annual average number of days with low-flows (śr$T_{95\%}$), 9 – annual maximum number of days with low-flows (max$T_{95\%}$), 10 – the lowest low flow, 11 – variation coefficient of low flow Nq (cv(Nq)), 12 – determination coefficient of statistically significant ($\alpha = 0.01$) linear trend of annual Nq low-flows, 13 – slope coefficient of statistically significant ($\alpha = 0.01$) linear trend of annual Nq low-flows

which deep groundwater reserves are drained. This is a rare phenomenon, therefore the variability of periodic outflows during a severe hydrological drought will be greater than that during a mild drought. The smallest variability of outflows $q_{95\%}$ and $q_{70\%}$ is characteristic for Warta River in Sieradz, due to the size of the catchment resources and the ineffectiveness in shaping low-flows on the main river and its tributaries.

The average annual number of days with low-flow $T_{95\%}$ is 16. The spatial variability of avg$T_{95\%}$ is low. The smallest value of this characteristic is noted at Widawka in Szczerców, where at the same time the highest ordinate of $q_{95\%}$ was recorded (see: Figure 3). In the same location, we also observe the smallest maximum number of days with this low-flow. Deep low-flows in this catchment are short-lived due to mine water discharges that affect them more strongly than the hydro-meteorological conditions. Low values of avg$T_{95\%}$ are also observed in Poraj (13 days) due to the maintenance of the guaranteed flow, however max$T_{95\%}$ is the largest here, reaching 160 days. As mentioned before, small lowland catchments are characterized by a high rate of recession of groundwater resources of the active exchange zone in drought conditions, therefore the outflows $q_{95\%}$ is such catchments last for a relatively long time (here: 16 days). The high value of max$T_{95\%}$ is present in the upland part of the catchment (Kule, Działoszyn), due to the high retention capacity and low susceptibility to groundwater recovery. Therefore, during a well-developed hydrological drought, the number of days with low-flows may be longer. Long max$T_{95\%}$ are also observed on Warta River in Sieradz (139 days) and in Nieciecz (126 days). The latter is of course related to human activity. Warta in Sieradz is characterized by outflows $q_{95\%}$ at the level of 2-3 $dm^3s^{-1}km^{-2}$, however, it is a catchment with low retention of the hydrologically active zone and the average susceptibility to renewing water resources (Jokiel 1994). These high values of max$T_{95\%}$ may concern the 1990s, when severe hydrological droughts occurred.

Outflow minima (NNq) also show spatial variation (see: Figure 3). The lowest value of NNq occurred in the Nieciecz catchment, where as a result of the impact of the depression cone, outflows drop down to 0.01 $dm^3s^{-1}km^{-2}$. Equally low minima characterize the remaining small lowland catchments – of Oleśnica and Grabia. A low NNq value is also characteristic of the Liswarta catchment, where in the upper part it reaches 0.33 $dm^3s^{-1}km^{-2}$, due to the low susceptibility to groundwater recovery. In addition, Liswarta River in its upper reaches is regulated, and at the beginning of the surveyed multi-year period, reclamation works were conducted there, which caused a lowering of the groundwater table (Fajer 2003, 2007). Higher NNq values occurred in large catchments with large water resources, such as Warta River up to Działoszyn and Warta River up to Sieradz. The highest NNq values were observed in the upper Widawka catchment, which – as a result of human activity – is resistant to the development of severe hydrological droughts. The coefficients of variation of annual outflows Nq are higher than in the case of periodic outflows $q_{70\%}$ and $q_{95\%}$, but their spatial distribution is similar. The biggest cv(Nq) values were found in small lowland catchments, and the smallest in catchments with large water resources, such as Sieradz and Działoszyn.

When analysing the Nq distributions in the studied catchment, one can notice their strong variation (see: Figure 4). Similar distribution of Nq is observed in the largest catchments with large water resources – Warta River up to Sieradz and Działoszyn. Slightly higher values are observed in Działoszyn, due to the higher retention capacity of underground water reservoirs, occurring in well-sealed karst rocks. Higher values can be seen in the Widawka catchment. It is characterized by the largest interquartile range. The maximum annual Nq can reach here almost 9 $dm^3s^{-1}km^{-2}$. The distribution of the studied characteristics in this catchment is asymmetrical, skewed to the right, which is associated with mine water discharges since 1975 as a result of dewatering of the deposit in the KWB "Bełchatów" mine. By this token, the low-flow from this catchment is larger. Along the course of Widawka, the impact of the economy conducted in the mine on the formation of Nq ordinates is observed. The Nq distributions in Rogóźno and Podgórze are similar to those for Szczerców. Right-skewed asymmetry is observed, however low-flows are smaller in this case. The smallest interquartile range and the lowest Nq values are noted in small catchments such as Oleśnica, Nieciecz and Grabia, as well as the catchment covered by anthropogenic pressure – the Warta River up to Poraj. The slightly asymmetric distribution, skewed to the left is characteristic of the Liswarta River catchment in Niwki, which is not observed on the water gauge in Kule, where the distribution is skewed to the right, and more similar to that in Działoszyn. Such structure of Nq in Niwki may be connected with the already mentioned regulation of the riverbed in the upper course of the river, and melioration works that took place at the beginning of the studied period (Fajer 2003, 2007).

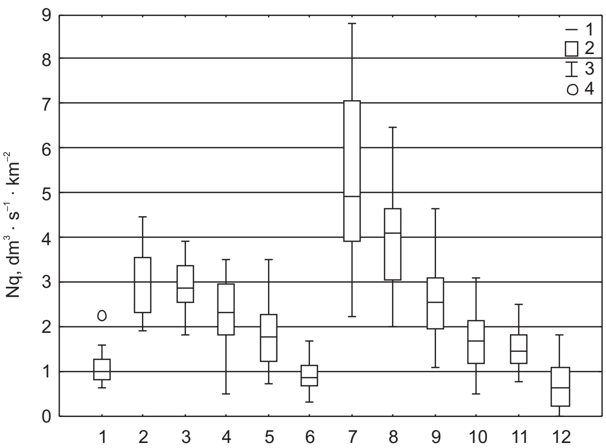

Fig 4. Distribution of Nq low flows in the upper Warta river catchment (1971–2000)
Nq – low flow, 1-4 – see fig. 2

In the study of the long-term variability of low-flows, for each sub-catchment, the existence of trends at the level of $\alpha = 0.01$ was verified. The analysis of systematic components in the long-term course of Nq led to the identification of linear trends, statistically significant for the majority of the catchments (see: Figure 3, Table 1). Significance was checked using the Student's T-Test and the Mann-Kendall Trend Test (Yule, Kendall 1966, Tomalski, Tomaszewski 2015). Trends are not statistically significant only in the catchments covered by anthropogenic pressure (Widawka and Warta up to Poraj), and for the Oleśnica catchment. Widawka and Warta in Poraj are characterized by a different degree of anthropogenic pressure. On the Widawka River, large Nq values are observed at the turn of the 1970s and 1980s, when drainage works were started at the "Bełchatów" KWB mine, whereas relatively low values are noted in the 1990s. In the Warta River catchment, up to Poraj, the Nq values are more evenly distributed, due to the economic activity conducted on the reservoir, therefore no statistically significant trend was observed. Neither of these catchments shows any trends, since water management has a much stronger impact than the hydro-climatic conditions. The lack of any tendencies in the Oleśnica catchment may also have anthropogenic background, associated with drainage or discharges of water from sewage treatment plants. In other catchments, there are significant negative trends, which indicate a relative decrease in low-flows in the surveyed multi-year period. The directional coefficients are relatively low, ranging from -0.065 in Niwki to -0.023 in Grabno. Trendline adjustment is also relatively small. Higher coefficients of determination are typical for the upland part of the catchment (Liswarta, Warta up to Działoszyn), and lower, for the lowland part (Warta up to Sieradz, and Grabia). The studied multi-year period is characterized by a large diversity of hydro-meteorological conditions. Within it, there are periods that almost completely free from low-flows (beginning and end of the studied period, and the turn of the 1970s and 1980s), but there are also dry periods, leading to severe hydrological droughts in the early 1990s (Tomaszewski 2012). A clear decline in minimum low-flows is observed until the 1990s, while after that, a certain increase is observed (see: Figure 5). Therefore, the observed trends should be interpreted with great caution, due to the relatively short time horizon of the research (namely, a period of 30 years).

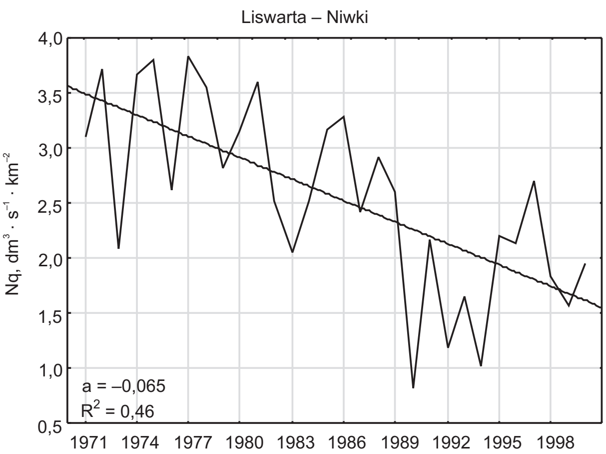

Fig. 5. Example of statistically significant negative linear trend in the Liswarta river catchment up to the water-gauge at Niwki
Nq – low flow

CONCLUSIONS

The periodic outflows $q_{70\%}$ and $q_{95\%}$, and also minimum outflows (NNq) show significant variation in the Upper Warta catchment. The analysis has shown that both their hydro-climatic and physiographic factors determine their spatial structure. The reservoirs of groundwater in the active exchange zone, as well as the size of watercourses, have significant impact on the spatial distribution of the surveyed characteristics. Differences were observed in the $q_{70\%}$, $q_{95\%}$ outflows and in NNq between lowland and upland areas. Much higher values characterized the latter part of the catchment, as a result of the drainage of karst and fissure-karst waters. The catchments in this area are characterized by high retention of the hydrologically active zone, whereas the susceptibility to groundwater recovery is average and low, which sometimes affects the increase in the number of days with low-flows. In the catchments with the largest water resources, relatively high values of periodic low-flows of little variability and a relatively high value of avg$T_{70\%,95\%}$. are observed. The lowest values of outflows $q_{70\%}$, $q_{95\%}$ and NNq and their greatest variability are observed in small lowland catchments due to limited hydraulic contact with the drained aquifers. Another group of factors significantly affecting the distribution of periodic outflows are water management activities, consisting mainly of drainage and water transfers in the "Bełchatów" KWB mine as well as the economic activity on the Poraj reservoir. The spatial variability of the average number of days with low-flows is low. Greater variation is observed for the maximum values of this characteristic. Both during mild and severe drought, the longest low-flows were recorded for the Warta in Poraj and Warta in Działoszyn, which is affected by the water management of the reservoir and the slow rate of renewing water resources in the upland part of the catchment. The lowest values are observed in the Widawka catchment, which – as a result of its water management – does not react to changes in climatic conditions. The decline in $q_{70\%}$, $q_{95\%}$ outflows and NNq was also influenced by hydro-climatic factors, namely the severe hydrological droughts of the 1990s, as evidenced by the analysis of trends in the long-term course of annual minimum outflows. The above-mentioned trends did not cover catchments under strong anthropogenic pressure.

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PRZESTRZENNA ZMIENNOŚĆ PRZEPŁYWÓW NIŻÓWKOWYCH W ZLEWNI GÓRNEJ WARTY

STRESZCZENIE

Przepływy niżówkowe stanowią ważny element reżimu rzecznego. Ich rozpoznanie poszerza wiedzę o kształtowaniu się zasobów wodnych w warunkach suszy. Przeprowadzone analizy miały na celu ocenę przestrzennej struktury tych przepływów. Obszarem badań była zlewnia Warty po wodowskaz w Sieradzu. Wejściowy materiał badawczy stanowiły serie przepływów dobowych z okresu 1971–2000 dla 12 wodowskazów zlokalizowanych w tej zlewni, udostępnione przez IMGW-PIB. W pierwszym etapie wyznaczono przepływy okresowe na bazie krzywej czasów trwania wraz z wyższymi oraz roczne przepływy minimalne. Ich wartości zostały przeliczone na odpływy jednostkowe, dzięki czemu możliwe były analizy porównawcze. Na podstawie uzyskanych wyników dokonano oceny przestrzennej zmienności przepływów niżówkowych w badanej zlewni. Dla wszystkich przekrojów zidentyfikowano roczną liczbę dni z przepływem niżówkowym. Ocenie poddano także dynamikę i rozkłady minimów przepływu, pojawiających się w okresie wieloletnim. Przeprowadzone analizy pozwoliły na wyodrębnienie czynników decydujących o strukturze przepływów niżówkowych. Wyniki badań zostały zilustrowane na stosownych mapach i wykresach.

Słowa kluczowe: odpływy charakterystyczne, przestrzenna zmienność odpływu, susza hydrologiczna