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SPATIAL VARIABILITY OF AVERAGE ANNUAL AND MONTHLY MINIMUM RIVER FLOW IN POLAND

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Abstract

The aim of this article is to analyse the spatial variability of *SNQ*, the average annual minimum river flow, as well as SNQ_m (m = 1, 2, …12), the average monthly minimum river flow in Poland.

The data were obtained from the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI) in the form of the daily flow series from the period between 01 Nov 1990 and 31 Oct 2020 from 433 gauging cross-sections located within the territory of Poland. The results of the analyses are presented on maps of the physiographic regions of Poland (the Coastlands, the Lakelands, the Lowlands, the Highlands, the Carpathians and the Sudety Mountains).

In order to compare SNq_m – the unit average minimum monthly flow between the physiographic regions, the Kruskal-Wallis test with the Dunn (Bonferroni) adjustment was performed. In order to evaluate the spatial variability of the SNq_m, the hypothesis was verified for each gauging station that the Spearman correlation coefficient between the SNq_m and the zero point of the gauge was different from zero.

The SNq_m flow changed over the year. As expected, the highest values were observed in March and April, and the lowest in July and August. Regardless of the month, the rivers in the central part of Poland (the Lowlands) were less water abundant than those in other regions of the country while the greatest flows were observed in the mountain rivers.

Statistically, no difference was observed between the SNq_m in the Coastlands, the Carpathians and the Sudety Mts., and in nearly all of the months between the SNQ_m in the Lakelands and the Lowlands.

In the whole territory of Poland, the river flow was dependent on the altitude of the catchment, while the strongest correlation was observed in the mountain regions.

Keywords: SNQ_m, average annual river flow, spatial variability, regional variability

PRZESTRZENNE ZRÓŻNICOWANIE ŚREDNIEGO MINIMALNEGO ROCZNEGO PRZEPŁYWU NA OBSZARZE POLSKI

Abstrakt

Celem pracy jest ocena przestrzennego zróżnicowania średniego minimalnego rocznego przepływu *SNQ*, a także przepływu SNQ_m (m = 1, 2, …12) w poszczególnych miesiącach w Polsce.

W pracy wykorzystano pozyskane z IMGW-PIB ciągi dobowych przepływów z okresu od 1.11.1990 do 31.10.2020 roku w 433 przekrojach wodowskazowych zlokalizowanych na obszarze Polski. Wyniki analiz przedstawiono na mapach na tle regionów fizycznogeograficznych (pobrzeża, pojezierza, niziny, wyżyny, Karpaty i Sudety).

Do porównania średnich SNq_m w każdym miesiącu, między regionami fizycznogeograficznymi wykorzystano test Kruskala--Wallisa z poprawką Dunna (Bonferroniego), a do oceny siły zróżnicowania przestrzennego przepływów SNq_m określono współczynnik korelacji Spearmana między SNq_m a wysokością położenia zera wodowskazu, a także zweryfikowano hipotezę o istotności tego współczynnika.

W ciągu roku przepływ SNq_m zmienia się; spodziewanie największe wartości obserwuje się w marcu i kwietniu, a najniższe w lipcu i sierpniu. Zdecydowanie najmniej zasobne w wodę są, niezależnie od miesiąca, rzeki środkowej i nizinnej części Polski, a największe przepływy obserwuje się w rzekach górskich.

Nie obserwuje się statystycznej różnicy między SNq_m na pobrzeżach, w Karpatach oraz Sudetach i w prawie wszystkich miesiącach między pojezierzami i nizinami.

Na obszarze Polski przepływ zależy od wysokości położenia zlewni, przy czym najsilniejsza zależność występuje w obszarach górskich.

Słowa kluczowe: SNQ_m, średni minimalny roczny przepływ, zróżnicowanie przestrzenne, zróżnicowanie regionalne

1. INTRODUCTION

One of the most crucial aspects involved in the preservation of water resources is ensuring that water organisms have optimal conditions to live. This issue has been found at the centre of many European directives and national legal acts. In Polish hydrology and water management, there is a notion of ‘characteristic flows’ which denotes the values of some flow characteristics at a river cross-section. Among such flows, the following may be distinguished: *SNQ* – the mean flow calculated from the minimum annual flows in a multiannual period and SNQ_m (m = 1,2, …, 12) – the mean monthly flow calculated from the monthly minimum flows in a multiannual period [1].

According to the Polish Water Law Act [2], the *SNQ* flow provides the basis for calculating the charges for water services and consumption. This cost consists of a fixed rate and a variable rate dependent on the amount of consumed surface water (art. 270, 271, 274). The rate for water services depends, respectively, on the amount of consumed water, water source (meaning whether the water has been sourced from the surface or underground), its intended use, and its average low flow from the multiannual period *SNQ*, whereby a multiannual period consists of at least 20 hydrological years [2] (article 270, point 6).

In Poland, the *SNQ* or SNQ_m flows are also used in calculating the minimum required flow and the ecological flow, as well as defining the streamflow drought (especially in older publications).

Streamflow drought is most commonly defined as a continuous period during which streamflow at a given cross-section is below Q_g, an assumed threshold flow [3, 4, 5, 6]. In their research, many Polish authors [4, 7–15] assume *SNQ* as the Q_g flow. Zielińska [16] defined streamflow drought as a continuous period during which streamflow at a given cross section is below the *SNQ* and distinguished summer and winter droughts, based on their origin. Summer streamflow droughts result from the prolonged lack of atmospheric precipitation, combined with high air temperatures and intense evaporation. Winter streamflow droughts, on the other hand, start in rivers at sub-zero air temperatures or result from the prolonged lack of precipitation during autumn (surface runoff stops because snowfall becomes retained on the surface). The lowest flows occur in frozen rivers.

The *SNQ* flow, as well as the minimum annual flows in the rivers of Poland, have been the subject of studies of several authors. Stachý at al. [17] proposed the direct method, the method based on multiple correlation and the methods based on interpolation and extrapolation of mean minimum flows while, Ozga-Zieliński and Walczykiewicz [1] carried out the analysis of the methods for calculating the *SNQ*. The methods depend on the length of the series in a multiannual period and physiographic catchment characteristics. Wałęga et al. [18] verified the applicability of the Punzet and Stachý formulas in several mountain catchments. Wałęga and Młyński [19] analysed the seasonality of the minimum flows, while Banasik et al. [20] proved the decrease of the *SNQ* value in the last 30-year period in two lowland catchments.

The minimum required flow Q_n was used in Poland since the 1960s. There are several definitions of Q_n in literature, for example by Kostrzewa [21], Witowski [22], the Małopolska school [23], the Wrocław school [24], Florkowski [23], or the National Foundation for Environmental Protection and Water Management [25]. The most commonly used definition is the one formulated by Kostrzewa [21] according to which the minimum required flow is the amount of water expressed in $m^3 \cdot s^{-1}$, which should be maintained as minimum in a given cross-section due to biological and social circumstances. This flow is defined based on two criteria [21]:

- the hydrobiological criterion – Q_n is calculated as the product of the *SNQ* flow and the coefficient dependent on the hydrological type of the river and its catchment area, and
- the fishing criterion aiming at estimating the necessary amount of water within a streambed needed for the ichthyofauna to develop well. The flow Q_n is determined based on the SNQ_m analysis in particular phases of the fish life cycle, for the following three phases during the year: spawning and reproduction, preying and the development of juvenile fish, and finally hibernation.

The *SNQ* flow also serves as the basis for calculating the minimum required flow in case of applying the methods by Florkowski or by the National Foundation for Environmental Protection and Water Management, whereas Stochliński utilizes the SNQ_m in the Małopolska method.

In Poland, the minimum required flow is currently a priority in terms of water use, which results from the regulations of the directors of the Regional Water Management Board (RWMB) who decide on the conditions on the use of water in particular water regions. It is the responsibility of all users under the concession to abide by them [2] (article 403, point 2, subpoint 11).

As aforementioned, there are several methods of calculating Q_n in Poland, however currently there is no one standardised methodology. Polish Water Law does not specify any definitions of the minimum required flow either. The values of this type of flow are, on the other hand, determined in two special cases [2] (article 403, points 7 and 8):

a) for permits required by the Polish Water Law Act granted for the needs of rearing or breeding of fish or other aquatic organisms – the minimum required flow should be at 50% of the *SNQ*,
b) and in case of using recycled water, the minimum required flow may be decreased by 50% of the *SNQ*.

The introduction of the term 'ecological flow' originates from the Water Framework Directive and Guidance Document No 31 [26]. This type of flow is defined in different ways. For example, Tharme [27] defines it as a flow which should remain within the river system or be supplied to it in order to maintain the good condition of water in the riverbeds, nearshore zones, marshes, floodplains or the river mouth.

Depending on the scale of the analysed location, available data, the time allocated for the assessment as well as the technical and financial capacity, it is possible to apply different methods of establishing the requirements of the ecological flow [28]. At the moment, in the world, over 200 methods of designing the ecological flow have been proposed. These methods may be divided into the following groups [27–31]: hydrological, hydraulic, habitat, holistic. Thanks to its simplicity, the most commonly used category of designing ecological flows in the world are hydrological methods which are based mainly on the historical flow series [28]. Hydrological methods are based on values such as: average flows (average annual or average low flow) or the values achieved from the flow duration curve at different time scales (annual, seasonal, or monthly) as well as the geomorphological characteristics of the catchment (area, stream gradient, etc.). One of the methods of this type is the simplified method by Kostrzewa based on the *SNQ*.

In Poland, ecological flow is defined for a bioperiod in a selected cross-section of the studied catchment as:

$Q_{e,b} = p_b \cdot SNQ_b \cdot A$, where: p_b is a tabularised value of the coefficient for control catchments, determined based on pilot studies for a given ichthyological type of river and particular bioperiods, SNQ_b is a unit average low runoff in the bioperiod determined by relating the SNQ_b of a given stream in a studied catchment to A, the catchment area *A* to cross-section [32].

To date, there have been a large number of publications on the subject of low flows and streamflow drought – some of them also on the scale of the whole country. For example, Stachý et al. [7, 8] assessed the magnitude of runoff in Poland and presented it, in form of maps, the average annual (*SNQ*) and the lowest annual (*NNq*) unit runoffs from the area of Poland from the 20-year period between 1951 and 1970.

Usually studies are carried out on a single river [12, 14, 15] or possibly several selected regions of Poland [33–35]. However, most of the older works were based on short multiannual periods and did not include a large number of stream gauges. This publication, unlike the aforementioned works, is based on complete and long daily series of flows from the last 30-year hydrological period, with data measured in over 400 cross-sections located throughout Poland.

Stachý et al. [7, 8] calculated the number of occurrences of flows lower than the *SNQ* in particular months for 180 gauging cross-sections. The month or the group of months with the highest number of flows lower than the *SNQ* was recognised as the typical period of occurrence of streamflow drought. Streamflow drought was divided into early-winter (November-December), winter (January-February), summer (June through August) and autumn (September-October). It was also observed that the lowest values of the SNq_m (below 0.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$) occurred in the region between the middle Oder and the middle Warta, the runoffs below 0.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$, dominate in the Lowlands, while in the uplands and the mountains – they do not exceed 0.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$. Runoffs below 1 $dm^3 \cdot s^{-1} \cdot km^{-2}$ occur primarily in the Sudety Mts. and the Carpathians, as well as in the Pomeranian Lakeland. Also, Zielińska [16] considered the region of the Polish Lowland as one of the greatest and long-lasting hydrological droughts.

The *SNQ* flow is, therefore, one of the most important hydrological characteristics necessary to complete hydrological documentation which form the basis of planning and design in terms of water engineering, preventing the effects of drought and managing the inland surface water resources, including granting administrative decisions [1].

The aim of this work is to analyse the spatial variability of the *SNq* and SNq_m (m = 1, 2, …12) – the unit average annual minimum flow *SNQ*, as well as the and the unit average monthly minimum river flow in Poland.

2. DATA AND METHODS

The series of average daily flows were used from the period between 1st November 1990 and 31st October 2020 (30 hydrological years) at 433 gauging cross-sections located throughout Poland. The data were obtained from the IMWM-NRI. The location of the cross-sections is presented in Fig. 1, on the map of Poland divided into physiographic regions based on Solon et al. [36]: the Coastlands, the Lakelands, the Lowlands, the Uplands, the Carpathians and the Sudety Mts. In order to compare the average flows in different gauging cross-sections, their values were standardised by dividing by the catchment areas.

The catchments analysed in this study were located throughout Poland. The area of the country is inclined from south east towards north west. The Lowlands are located in the north and central Poland, whereas the mountains and the Highlands in the south.

Lowland terrain dominates in Poland – approximately 75% of its area is located below 200 m a.s.l. The most of the gauges (311 out of 433) were located in the lowlands, out of which three lay below the sea level (Tczew on the Vistula, Trzebiatów on the Reda and Bągart on the Elbląg). 111 gauges were highland cross-sections (located at the altitudes between 200 and 500 m a.s.l.), whereas the remaining 11 lay in the mountains. The gauge located at the highest altitude was Jakuszyce on the Kamienna (H = 849.5 m a.s.l.). The catchment areas decreased as the altitudes of the location of the zero points of gauges increased, as the Spearman rank correlation coefficient was -0.369 and was statistically significant (Fig. 2).

Approximately a quarter (119 out of 433) of catchments had areas below 300 km^2, which means they may be considered small. The areas of the 140 out of 314 catchments were below 1,000 km^2. Several very large catchments were analysed in this study – the areas of 42 catchments were above 10,000 km^2, while there were 12 catchments with the area exceeding 50,000 km^2.

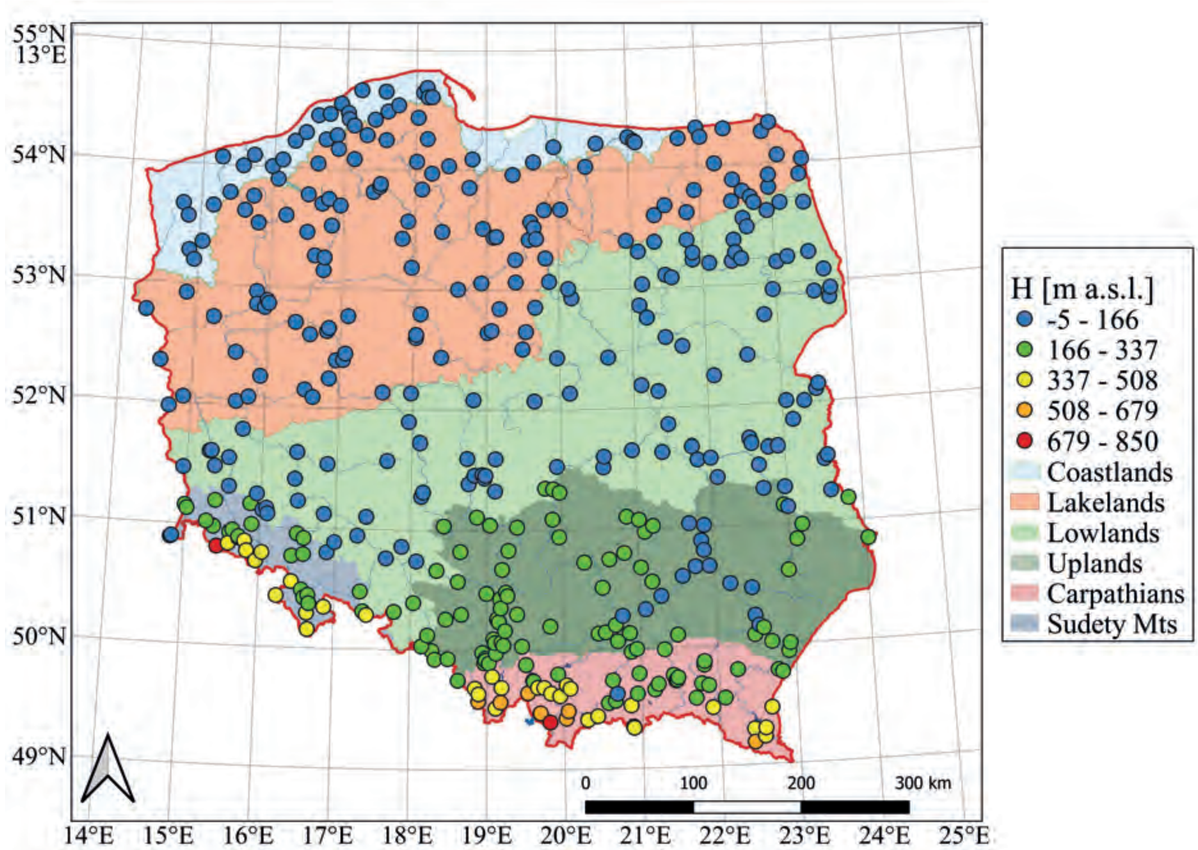

Fig. 1. Location of gauging cross-sections in Poland with information on the gauging station elevation *H* [m a.s.l] based on physiographic regions according to the regionalization of Solon et al [36]

Ryc. 1. Położenie wodowskazów w Polsce wraz z informacją o wysokości *H* położenia zera tych wodowskazów, *H* [m n.p.m.] na tle regionów fizycznogeograficznych, zgodnie z regionalizacją Solona i in. [36]

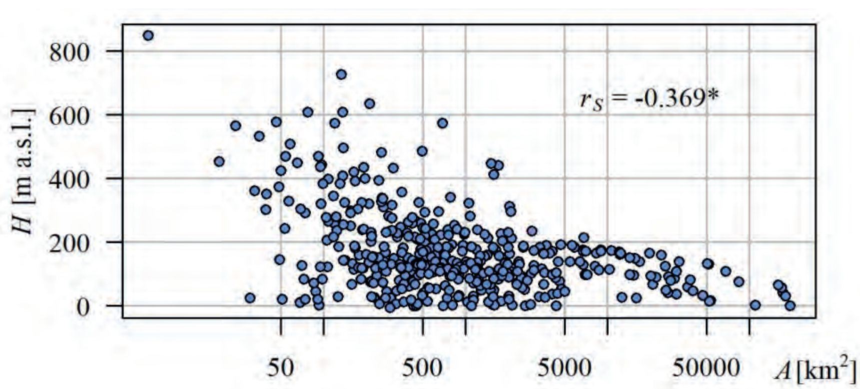

Fig. 2. Scatterplot that shows the relationship between catchment area *A* and gauging station elevation *H*; r_S is a Spearman correlation coefficient, asterisk * means a significant correlation (at the significance level $\alpha = 0.05$)

Ryc. 2. Wykres rozrzutu przedstawiający zależność powierzchni zlewni *A* zamkniętej przekrojem wodowskazowym od wysokości *H* położenia zera tych wodowskazów; r_S jest współczynnikiem korelacji Spearmana, a symbol * oznacza korelację istotną statystycznie (na poziomie istotności $\alpha = 0.05$)

Based on the series of daily flows, the series of monthly minimal flows was obtained, first for each month separately, $m = 1, 2, ..., 12$. Then the unit average monthly minimum flow SNq_m, $m = 1, 2, \ldots, 12$ was computed by division of the average value of these minima by the catchment area. These flows were superimposed on the map of Poland divided into physiographic regions [36] and global regional average SNq_m^{mean}, minimum SNq_m^{min} and maximum SNq_m^{max} values observed in physiographic regions were also determined. The average annual minimum flow SNQ was also calculated, and then the unit average annual minimum flow SNq was computed as the division of SNQ by the catchment area.

For each month, the SNq_m were compared between physiographic regions [36] using the Kruskal-Wallis test with Dunn (Bonferroni) adjustment at the significance level of $\alpha = 5\%$.

The Kruskal–Wallis rank sum test is a non-parametric method for testing whether samples originate from the same distribution. The null hypothesis for this test is that there is no difference in the median values of the considered groups and the alternative hypothesis is that at least one population median of one group is different from the population median of at least one other group. If the results of a Kruskal-Wallis test are statistically significant, then it is appropriate to conduct post hoc test (Dunn's test) to determine exactly which groups are different [37].

The Bonferroni adjustment is a method that allows many comparison statements to be made while still assuring the overall confidence coefficient is maintained [38]. If multiple hypotheses are tested, the probability of observing a rare event increases, and therefore, the likelihood of incorrectly rejecting a null hypothesis (and making a type I error) increases. The Bonferroni correction compensates for that increase by testing each individual hypothesis at a significance level of α/m, where α is the desired overall alpha level and m is the number of hypotheses.

For the evaluation of the spatial variability of the SNq_m flows, the Spearman correlation coefficient was calculated between the SNq_m and the zero point of the gauge. The hypothesis that the coefficient is different from zero was also verified.

All statistical calculations were performed using the GNU R software package [39]. For all the tests considered in the paper, the significance level $\alpha = 0.05$ was assumed.

3. RESULTS

In each of the 433 studied gauging cross-sections, the unit average monthly flows SNq_m, $m = 1, 2, \ldots, 12$ were calculated. For each month, a spatial distribution of SNq_m was depicted on the map of Poland with physiographic regions (Fig. 3 and 4). In each month, the range of SNq_m was divided into five categories and a histogram of SNq_m was also plotted. In order to compare the maps, the ranges of SNq_m values divided into five categories are marked blue, green, yellow, orange and red (from the lowest to the highest SNq_m values).

During year, the SNq_m changed expectedly. The highest average area values of SNq_m occurred during the time of spring thaw – in March and April (the medians of SNq_m in these months were above 5.5 $dm^3s^{-1}km^{-2}$, while the average values – approximately 6.3 $dm^3s^{-1}km^{-2}$). In turn, the lowest values were observed in summer and autumn – between July and September (the medians of SNq_m in these months were above 2.7–2.8 $dm^3s^{-1}km^{-2}$, while the average values – 3.2–3.6 $dm^3s^{-1}km^{-2}$) (Fig. 5).

Regardless of the month, the most of the observed SNq_m flows belonged to the two first categories (blue and green spots on maps and blue and green bars in histograms). In January, February and March, these flowsmade up between 75 and 82% of all flows, in September, October, November and December between 85 and 88%, whereas in the remaining months – between 92 and 98%.

In all months, the lowest average SNq_m flows were observed in the Lowlands (boxplots in Figures 3 and 4), higher values were observed in the Lakelands and the Uplands, and the highest ones – in the Coastlands, the Carpathians and the Sudety Mts.

In all of the maps, the highest SNq_m flows occurred rarely (red spots). Their fraction was not above 0.9% of all flows, while their values substantially exceeded the SNq_m values in the remaining part of Poland. Such values were also observed in higher parts of the mountains.

High values of the SNq_m (red, orange and yellow spots in the maps – Fig. 3 and 4) were usually observed in the south and south-western part of the country, as well as in the north of Poland. The lowest values of the SNq_m occurred mostly in the central part of Poland. Because the land elevation throughout the country increases from north-west towards the south, it may seem

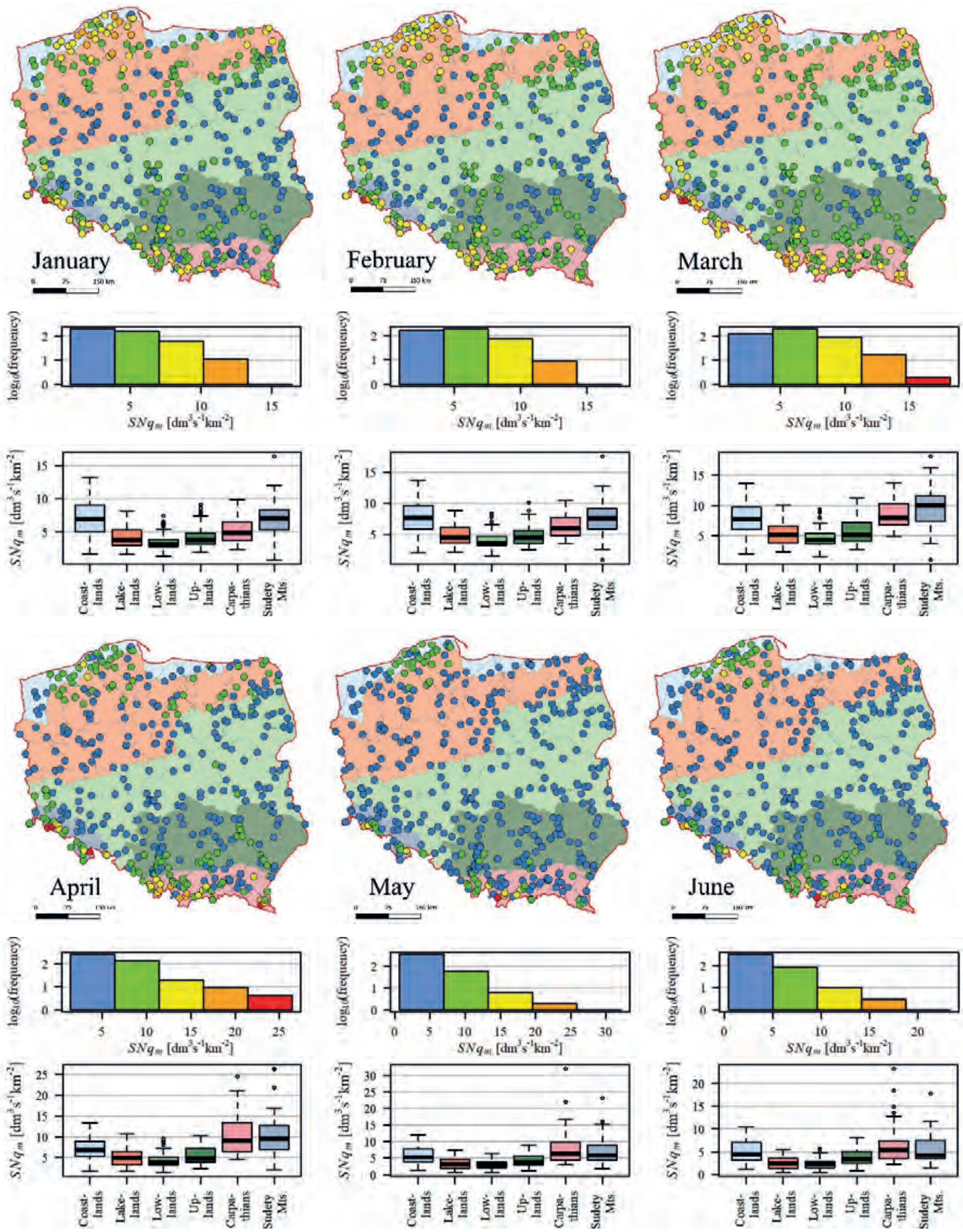

Fig. 3. Spatial distributions of the average monthly SNq_m flow in Poland, from January to June, along with histograms and box-whisker plots for individual physiographic regions; the colours of the gauging stations (points on the map) correspond to the colours of histogram bars, and the colours of regions correspond to the colours of boxplots

Ryc. 3. Przestrzenne rozkłady średnich miesięcznych przepływów SNq_m na obszarze Polski od stycznia do czerwca wraz z histogramami i wykresami typu pudełko-wąsy dla poszczególnych regionów fizycznogeograficznych; kolory stacji wodowskazowych odpowiadają kolorom na histogramach, a kolory regionów – kolorom na wykresach typu pudełko-wąsy

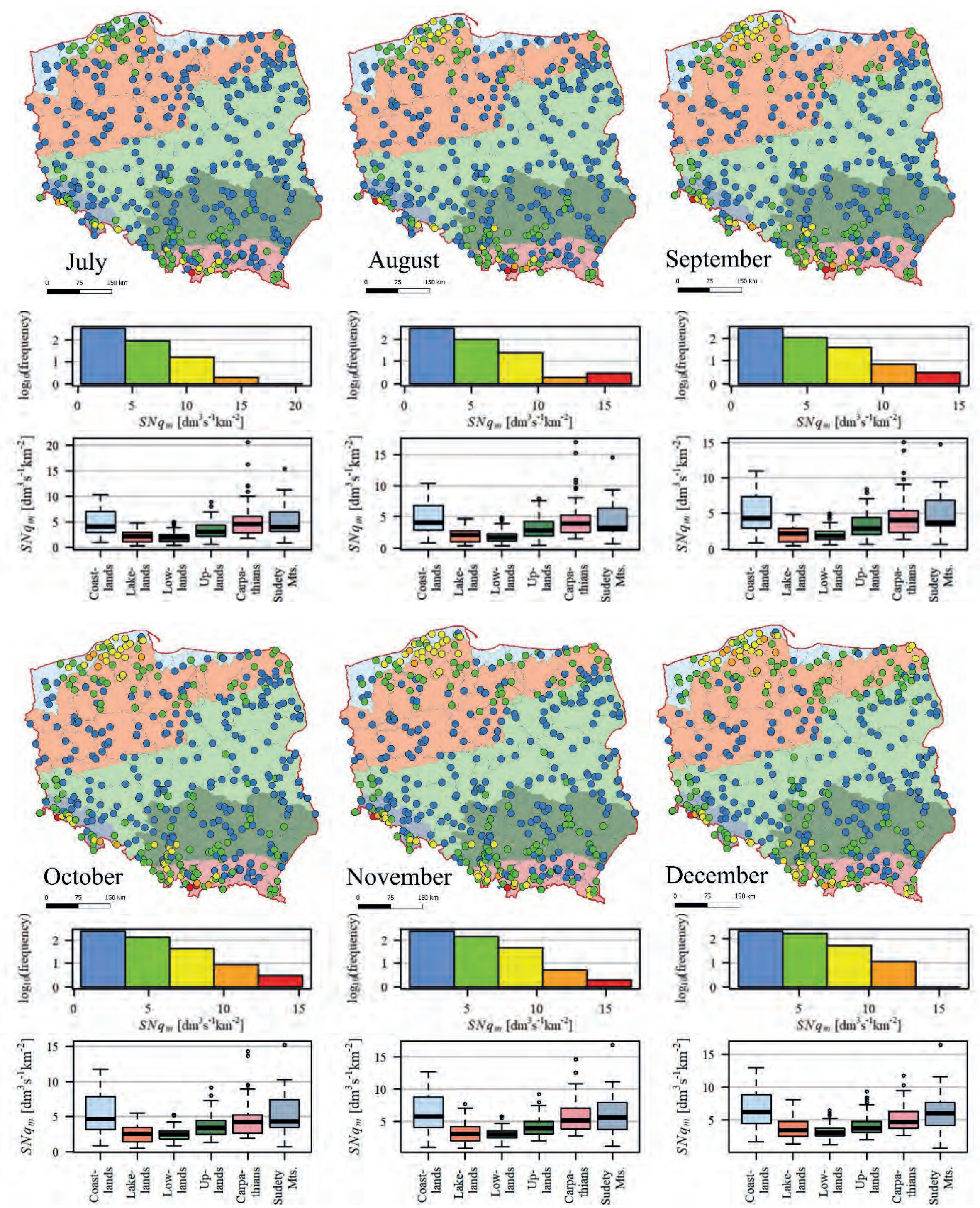

Fig. 4. Spatial distributions of the average monthly SNq_m flow in Poland, from July to December, along with histograms and box-whisker charts for individual physiographic regions; the colors of the gauging stations (points on the map) correspond to the colors of histogram bars, and colors of regions correspond to colors of boxplots

Ryc. 4. Przestrzenne rozkłady średnich miesięcznych przepływów SNq_m na obszarze Polski od lipca do grudnia wraz z histogramami i wykresami typu pudełko-wąsy dla poszczególnych regionów fizycznogeograficznych; kolory stacji wodowskazowych odpowiadają kolorom na histogramach, a kolory regionów – kolorom na wykresach typu pudełko-wąsy

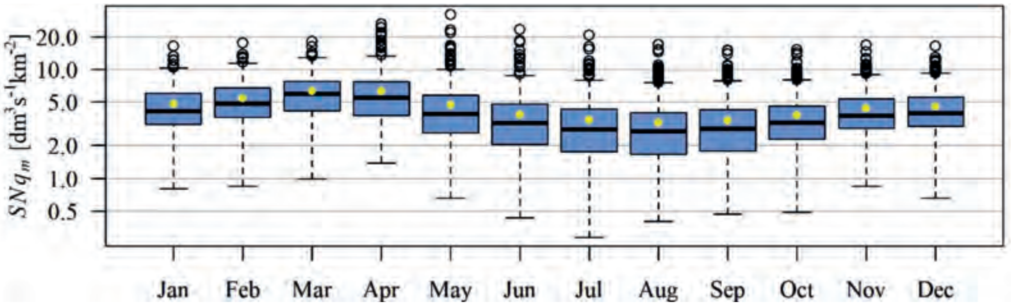

Fig. 5. Distribution of the average monthly SNq_m flow in Poland
Ryc. 5. Rozkład średniego miesięcznego przepływu SNq_m na obszarze Polski

Table. 1. The Spearman correlation coefficient between SNq_m and H; asterisk * shows a significant correlation (at the significance level $\alpha = 0.05$)
Tabela 1. Współczynnik korelacji Spearmana między SNq_m a wysokością położenia zera wodowskazu; * oznacza korelację istotną statystycznie (na poziomie istotności $\alpha = 0.05$)

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
r	0.065*	0.081*	0.219*	0.256*	0.246*	0.276*	0.250*	0.213*	0.202*	0.197*	0.187*	0.106*

that the correlation between the SNq_m and the elevation should not be high. Indeed, the Spearman correlations between SNq_m and the altitude of the zero point of the gauges were not high, however in all months, they were positive and statistically significant (Table 1).

The maximum of the average regional values of SNq_m, were observed in the Carpathians and the Sudety Mts. in April; in the remaining regions – in March, while the minimum occurred in all of the regions in August (Fig. 6a). The highest regional values of the SNq_m exceeded 10 dm^3·s^{-1}·km^{-2} in the Carpathians and the Sudety Mts., which in terms of the figures were nearly 8 dm^{3}s^{-1}km^{-2} in the Coastlands, approximately 5 dm^3·s·km^{-2} in the Lakelands and the Uplands, and below 5 dm^{3}s^{-1}km^{-2} in the Lowlands.

The maximum of the lowest regional values of the SNq_m was observed in March, while in the Uplands in April. The minimum values were observed in July (the Lowlands and the Lakelands), August (the Uplands) and September (the Carpathians, the Sudety Mts. and the Coastlands) (Fig. 6b). It can also be observed that the values of the highest minimum (regional) SNq_m in the Carpathians were significantly higher during the whole year than anywhere else in Poland.

The highest regional values of the SNq_m, observed in the Carpathians and the Sudety Mts., were markedly higher compared to other regions, whereas during the months of thaw, they exceeded 25 dm^{3}s^{-1}km^{-2} (Fig. 6c).

In order to better visualize the variability of the SNq_m during year, the number of gauging stations with the lowest (Fig. 7a) and the highest (Fig. 7b) values of the SNq_m was computed for each month separately.

As expected, the largest number of gauges (in all regions) showed the minimum values of the SNq_m at the end of summer (in all regions, most frequently in August), while the maximum values of the SNq_m were found at the beginning of spring (in all regions, most frequently in March).

Regardless of the month, the lowest average SNq_m flows were observed in the Lowlands (boxplots in Figures 3 and 4), while higher ones were in the Lakelands and the Uplands, and the highest – in the Coastlands, the Carpathians and the Sudety Mts.

In order to verify whether the SNq_m differed significantly in particular regions, the Kruskal-Wallis test was applied. In all of the months, the *p*-value of the test was below 2.20E-16 (Table 2) which implies that in all months the SNq_m differed between the six regions.

In order to recognize the pairs of regions where the medians of the SNq_m differed, the post-hoc Dunn test (with Bonferroni adjustment) was applied. Results were given in Table 2.

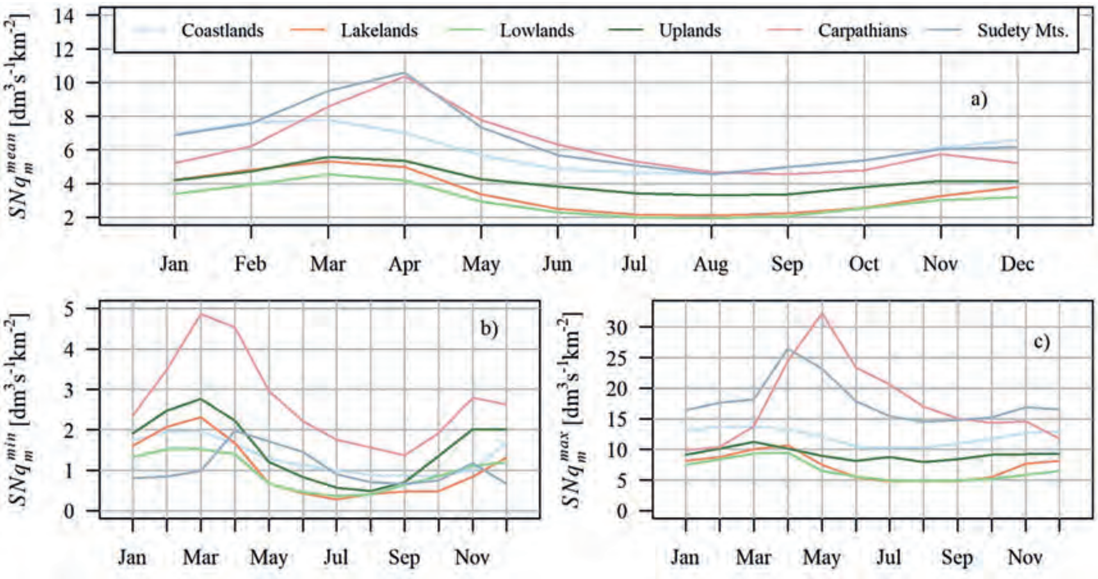

Fig. 6. SNq_m values: a) average, b) the lowest, c) the highest observed in particular physiographic regions
Ryc. 6. Wartości SNq_m: a) średnia b) najmniejsza, c) maksymalna zaobserwowana w poszczególnych regionach fizycznogeograficznych

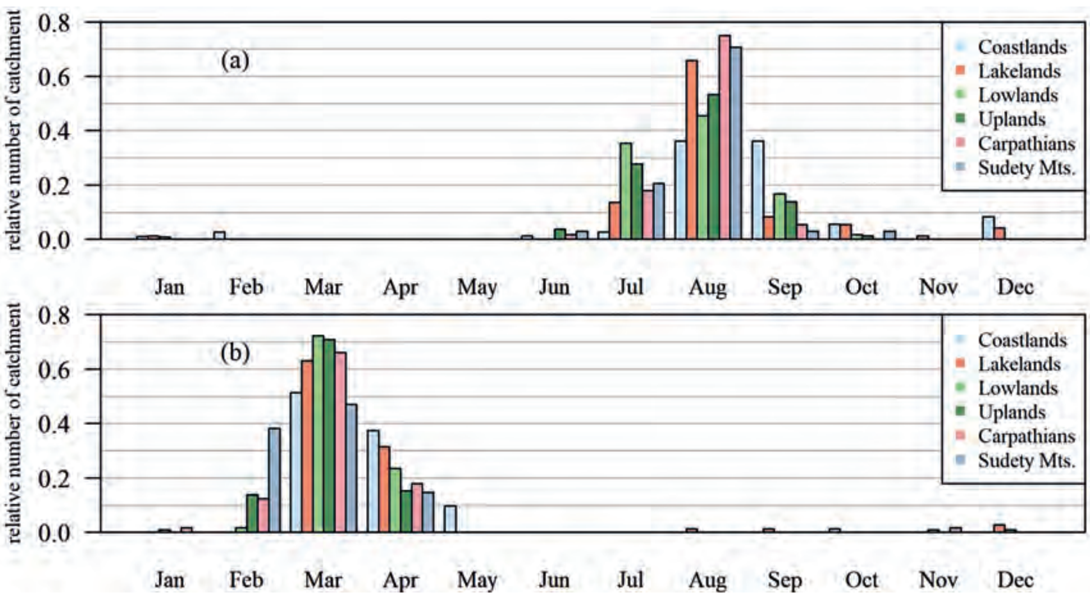

Fig. 7. The relative number of catchments with (a) the lowest and (b) the highest values of the SNq_m in physiographic regions
Ryc. 7. Względna liczba zlewni, w których zaobserwowano: (a) najmniejszą wartość SNq_m, (b) największą wartość SNq_m w regionach fizycznogeograficznych

In 61 out of 180 analysed cases (15 paired regions × 12 months) it was confirmed that the SNq_m flows did not differ between regions. No difference was shown in all months between the median of the SNq_m in the Coastlands, the Carpathians or the Sudety Mts. In most of the year (apart from January and February), there was no difference either between the SNq_m in the Lakelands and Lowlands. Interestingly, for most of the year the significant difference between median SNq_m can be observed in the Uplands and the Mountains (Uplands – Carpathians from November to July, and Uplands – Sudety Mts. from November to May).

Table 2. The results of the Kruskal-Wallis test (the last two lines) and the *p*-values of the multiple comparison post-hoc Dunn test with the Bonferroni adjustment; the *p*-values less than 0.05 proved of significant differences between the SNq_m median among the physiographic regions in particular months

Tabela 2. Wyniki testu Kruskala-Wallisa i testu wielokrotnych porównań post-hoc Dunn z poprawką Bonferroniego (wartości *p*); wartości *p* mniejsze niż 0.05 świadczą o istnieniu istotnych różnic między medianą SNq_m pomiędzy regionami fizyczno-geograficznymi w konkretnych miesiącach

No	Regions	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Coastlands – Lakelands	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	Coastlands – Lowlands	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	Lakelands – Lowlands	0.011	0.008	0.143	0.123	0.848	1.000	1.000	1.000	1.000	1.000	1.000	0.127
4	Coastlands – Uplands	0.000	0.000	0.000	0.001	0.010	0.234	0.094	0.040	0.009	0.012	0.000	0.000
5	Lakelands – Uplands	1.000	1.000	1.000	1.000	0.094	0.000	0.000	0.000	0.001	0.001	0.020	1.000
6	Lowlands – Uplands	0.018	0.025	0.006	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
7	Coastlands – Carpathians	0.056	0.371	0.852	0.048	0.515	0.654	1.000	1.000	1.000	1.000	1.000	0.258
8	Lakelands – Carpathians	0.026	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	Lowlands – Carpathians	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	Uplands – Carpathians	0.012	0.000	0.000	0.000	0.000	0.001	0.012	0.071	0.166	0.271	0.001	0.010
11	Coastlands – Sudety Mts.	1.000	1.000	0.756	0.228	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
12	Lakelands – Sudety Mts.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	Lowlands – Sudety Mts.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	Uplands – Sudety Mts.	0.000	0.000	0.000	0.000	0.002	0.094	0.161	0.386	0.042	0.066	0.011	0.000
15	Carpathians – Sudety Mts.	0.197	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Kruskal-Wallis	statistic	139.4	151.5	168.8	156.8	139.4	143.0	142.5	132.7	132.3	118.1	140.0	133.9
	p-value	< 2.20E–16											

4. SUMMARY AND DISCUSSION

The differences between geophysical regions in the SNQ_m are mainly triggered by the spatial variability of precipitation that is usually higher in Lakelands and Coastlands than in Lowlands. This relation can be observed mainly in winter months (Figures 3 and 4).

The central part of Poland is dominated by the Warta River in the west and the Wieprz River in the east, together with their tributaries. However both river basins are under stress of permanent water scarcity due to very low precipitation and intensive water use for industrial and agriculture purposes (Warta), and intensive agriculture production and steppization (Wieprz). These factors are the main causes of very low SNQ_m values in all months in the belt that comprises of the western part of the Lakelands and Lowlands and the eastern part of the Lowlands.

High SNQ_m, values were observed in the Carpathians which follows from the affluence of aquifers. Bartnik [40] notes that the main characteristic of the Carpathian area is that the major role is played by precipitation and evaporation processes in the formation of runoff (as compared with other parts of Poland). In the southern part (the Carpathians and the Sudety Mountains) the SNQ_m was relatively high at the end of winter and beginning of spring. This might be explained by mountain snowpack melting that contributes to the increase of river discharges in the region.

Various methods of analyzing very low river flows are used around the world. In the USA, the most widely used river flow is $7Q_{10}$, which is defined as the lowest 7-day average with 10-year return period, using daily discharge data [41]. In Europe, most commonly used flows with the probability of exeedance equalling 70%, 90%, 95% [42]. In Russia the widely used indices are 1-day and 30-day summer and winter low flows [43].

Our results are based on continuous time series data recorded at 433 stations. However, other databases that were generated using novel methods based on artificial intelligence, namely neural network algorithms, can be also used in the future [44–46], for example, in the USA National Water Model (NWM) retrospective simulations are used [47]. Such databases have a very fine spatial resolution and a global spatial coverage. As regards the *SNQ* flows in the territory of Poland, such databases can be used at places without river flow measurements, e.g. in assessing the risk of drought.

For the purpose of this study, a much larger number of gauges, as compared to previous works, was used and the *SNq* and SNq_m flows were determined in rivers from six physiographic regions in Poland: the Coastlands, the Lakelands, the Lowlands, the Uplands, the Carpathians and the Sudety Mts.

During the year, the SNq_m changed. In March, thaw is observed in the whole country, however it is different in various regions which influenced the variability of SNq_m. The SNq_m in March reached its maximum value in the Coastlands, the Lakelands, the Lowlands, and the Uplands, however it was not yet the highest in the mountains. In April the thaw water runoff could be still observed in Poland, whereas the highest SNq_m values were noticed in the Carpathians and the Sudety Mts. In May, after the thaw wave had passed, the SNq_m, decreased in the whole country. The lowest values of the SNq_m occurred in the Lakelands and the Lowlands however, a large runoff was still observed in the mountains where thaw water was running down. In the following months, especially in central Poland, the SNq_m values decreased which was the result of the lowering of precipitation, increasing air temperatures, evaporation and transpiration. In the whole country, the smallest values SNq_m were observed in August, when the average regional SNq_m reached their annual minimum. In September, average runoffs increased their values to a small degree, which was the result of the autumn precipitation and low evaporation (especially in mountains). In winter in the Carpathian and the Sudety Mts., long streamflow droughts often occurred, while in the remaining areas – mainly in the Lowlands and the Lakelands – low levels of rivers persisted. In October, streamflow droughts did not occur in such a large part of the country, which was mainly due to the lower loss for evaporation. In the next months (November, December, January), the runoffs increased. However, in the Sudety Mts. and Carpathians, the increase in SNq_m was not very high because a part of precipitation was accumulated as snowfall. In February, thaw began in the whole of the country which intensified the runoff. In mountains, owing to the persisting low temperatures, runoff increased later.

Similar conclusions were drawn by Bartnik [11] who observed that the highest SNq_m in Poland occurred in the early spring – mainly in March, while the lowest – mainly towards the end of summer (in August), and in the Sudety Mts. at the turn of August and September.

Stachý et al. [7], in turn, emphasised that in Poland summer and autumn streamflow droughts were predominant, whereas early-winter and winter ones occurred mostly in the Upper Vistula catchment.

The rivers of the central part of Poland (the Lowlands) were significantly the least abundant in water, while the greatest flows were observed in the mountain rivers as well as the rivers of the Coastlands.

5. CONCLUSIONS

The spatial and temporal distribution of extremes are very important in analyses of low flow, including *SNQ*.

This paper is a continuation of the research on the temporal and spatial variability of characteristic flows (monthly, annual) in Polish rivers, in regional approach. In the previous article [48], it was shown, among others, that average unit flows are statistically significantly positively correlated with the height of the water gauge (with the highest values in the mountains and in the Coantlands). Usually the smallest SNQ_m occurred in the central Poland – in Wielkopolska and in the Mazowsze Lowland as well, and the largest values were in the Mountains and in the Coastlands. Interestingly, there was no significant difference in the SNq_m between the Coastlands, the Carpathians and the Sudety Mts. In most months (all apart from January and February) the difference was not significant between the Lakelands and the Lowlands. Because of the relatively high flows in the Coastlands, the average low flow in each of the months was not very strongly correlated with the altitude (however significantly and positively). This means that in the whole of Poland the flow depended on the location of the catchment, while the strongest correlation occurred in the mountain areas. It appears that the distribution of SNq_m depends not only on the climatic conditions, but it results from overlapping hydrogeological and climatic conditions with anthropogenic activity.

The maps presented in this work can also be used as a background to more detailed interregional analysis. Research results can also be applied in various designs and tasks relating to determining to the volume and use of water resources.

REFERENCES

1. Ozga-Zieliński, B.; Walczykiewicz T. Metody obliczania przepływu średniego niskiego SNQ. Seria Publikacji Naukowo-Badawczych IMGW-PIB, Monografia, Warszawa, 2022 (in Polish).
2. Prawo Wodne (Ustawa z dnia 20 lipca 2017 r., Dz. U. 2017, poz. 1566) – Polish Water Law (Act of 20 July 2017, Journal of Laws of 2017, item 1566).
3. Zielińska, M.; Statistical methods of working out low flows. Geophysical Review, 1963, VIII (XVI), 1–2, pp. 75–87.
4. Ozga-Zielińska, M.; Brzeziński J. Applied hydrology. PWN, Wyd. 2, Warszawa, 1997.
5. Smakhtin, V. U. Low flow hydrology: a review. J. Hydrol., 240, 2001, pp. 147–186.
6. Tallaksen, L.M.; van Lanen, H.A.J. Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Sciences 48. Elsevier B.V., 2004, pp. 580.
7. Stachý, J.; Biernat, B.; Dobrzyńska, I. Odpływ rzek polskich w latach 1951–1970. IMGW, Warszawa, 1979 (in Polish).
8. Stachý J.; Fal, B.; Orsztynowicz, J. Odpływ rzeczny. [in:] Stachý J. (eds.) Atlas hydrologiczny Polski. IMGW, tom 2, Wydawnictwa Geologiczne, Warszawa, 1986, pp. 229–521 (in Polish).
9. Farat, R.; Kępinska-Kasprzak, M.; Kowalczak, P.; Mager, P. Droughts in Poland, 1951–90. Drought Network News (1994–2001), 1998, pp. 42.
10. Mager, P.; Kuźnicka, M.; Kępińska-Kasprzak, M.; Farat, R. Changes in the intensity and frequency of occurrence of droughts in Poland (1891–1995). Geographia Polonica, 73, 2. Autumn 2000 Pl, 2000, pp. 41–48.
11. Bartnik, A. Low flow in Poland. Acta Geographica Lodziensia nr 91, Łódzkie Towarzystwo Naukowe, 2005.
12. Bartczak, A. Long-term variability of the river outflow from Zgłowiączka basin. Polska Akademia Nauk, Geographical Studies, 2007, pp. 209.
13. Fal, B. Niżówki na górnej i środkowej Wiśle. Gospodarka Wodna, 2, 2007, pp. 72–81 (in Polish).
14. Kaznowska, E.; Banasik, K. Intensity of streamflow droughts in small agricultural catchment of Mazowiecka Lowland in last 45 years. Acta Scientiarum Polonorum, Formatio Circumiectus 8 (3–4), 2009, pp. 5–16.
15. Kubiak-Wójcicka, K.; The characteristics of low water levels on the Vistula River in Toruń. [in:] Marszelewski W. (eds.) Water management in a changing environment. Monografie Komisji Hydrologicznej Polskiego Towarzystwa Geograficznego, Nicolaus Copernicus University in Toruń, 2012, pp. 85–93.
16. Zielińska, M.; Statistical methods of working out lows – I. Przegląd Geofizyczny, VIII (XVI), 1–2, 1963, pp. 75–87.
17. Stachý, J.; Biernat, B.; Bondarczuk, Z.; Czarnecka, H.; Dobrzyńska, H.; Fal, B. Zasady obliczania przepływów średnich niskich rzek polskich. IMGW Warszawa, 1991 (in Polish).
18. Wałęga, A.; Młyński, D.; Kokoszka, R. Verification of selected empirical methods for the calculation of minimum and mean flows in catchments of the Dunajec basin. Infrastructure and Ecology of Rural Areas, II/3/2014, 2014.
19. Wałęga, A.; Młyński, D. Assesment of Seasonal Occurance of Minimum Flow for Mountain River by Colwell Indicies, Infrastructure and Ecology of Rural Areas, II/2/2016, 2016.
20. Banasik, K.; Kaznowska, E.; Letkiewicz, B.; Wasilewicz, M. Analysis of selected hydrological characteristics of two small lowland catchments, Acta Scientiarum Polnorum Formation Circumiectus 21 (1), 2022, pp. 33–47.
21. Kostrzewa, H. Weryfikacja kryteriów i wielkości przepływu nienaruszalnego dla rzek. Mat. Bad. IMGW, Gospodarka wodna i ochrona wód, 1977 (in Polish).
22. Witowski, K.; Filipkowski, A.; Gromiec, M.J. Obliczanie przepływu nienaruszalnego – poradnik. Warszawa: IMGW, 2008 (in Polish).
23. Gręplowska, Z.; Stochliński, T. Minimum acceptable flow. Part I, Rudiments. Technical Transactions. 15-Ś, 2004, pp. 59–96.
24. Młostek, E.; Malicka, J. Próba zastosowania i ocena określenia przepływu nienaruszalnego w oparciu o metodykę zastosowaną na Nysie Łużyckiej do rzeki Kaczawy o odmiennych warunkach hydrologicznych i zagospodarowania (wg kryterium hydrologicznego), IMGW/o. Wrocław, typescript, 1999 (in Polish).
25. Więzik, B. Metody określania przepływu nienaruszalnego – zalety i wady. Stowarzyszenie Hydrologów Polskich, RZGW Seminar in Kraków, 25.11.2013, 2013 (in Polish).
26. European Commission: Ecological flows in the implementation of the Water Framework Directive. CIS guidance document nº 31. Technical Report – 2015 – 086. European Union, 2015.
27. Tharme, R.E. A global perspective on ecological flow assessment: emerging trends in the development and application of ecological flow methodologies for rivers. River Research and Applications, 19(5–6), 2003, pp. 397–441.
28. Acreman, M. Environmental flows – basics for novices. WIREs Water, 3, 2016, pp. 622–628, doi: 10.1002/wat2.1160.
29. King, J.; Brown, C. Environmental flows: strikingthe balance between development and resource pro-tection.Ecology and Society,11, 2006, pp. 26.
30. Armas-Vargas, F.; Escolero, O.; García de Jalón, D.; Zambrano, L.; González del Tánago, M.; Kralisch, S. Proposing environmental flows based on physical habitat simulation for five fish species in the Lower Duero River Basin, Mexico. Hidrobiológica Ago, Volume 27, 2, 2017, pp. 185–200.

31. MGGP. Materiały Konferencji, Wdrożenie metody szacowania przepływów środowiskowych w Polsce, 21.03.2018, Warszawa, 2018 (in Polish).
32. KZGW.: Wdrożenie metody szacowania przepływów środowiskowych w Polsce. Weryfikacja i kalibracja metody szacowania przepływów środowiskowych – metodyka i część terenowa. Zad. 1.1.3 Metodyka weryfikacji i kalibracji metody szacowania przepływów środowiskowych, Krajowy Zarząd Gospodarki Wodnej, 2017 (in Polish).
33. Ziemońska, Z. Hydrographic conditions in the Polish Western Carpathians. Geographical Studies No 103, PAN, Institute of Geography, 1973.
34. Tomaszewski, E. Multiannual and seasonal dynamics of low flows in rivers of central Poland. Wydawnictwo Uniwersytetu Łódzkiego, 2012 (in Polish).
35. Baran-Gurgul, K. The spatial and temporal variability of hydrological drought in the Polish Carpathians. Journal of Hydrology and Hydromechanics, 70, 2, 2022, pp. 156–169, doi: 10.2478/johh-2022-0007.
36. Solon, J.; Borzyszkowski, J.; Bidłasik, M.; Richling, A.; Badora, K.; Balon, J.; Brzezińska-Wójcik, T.; Chabudziński, Ł.; Dobrowolski, R.; Grzegorczyk, I.; Jodłowski, M.; Kistowski, M.; Kot, R.; Krąż, P.; Lechnio, J.; Macias, A.; Majchrowska, A.; Malinowska, E.; Migoń, P.; Myga-Piątek, U.; Nita, J.; Papińska, E.; Rodzik, J.; Strzyż, M.; Terpiłowski, S.; Ziaja W. Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geogr. Pol., 91, 2, 2018, pp. 143–170.
37. Dunn, O. J. Multiple comparisons using rank sums. Technometrics, 6(3), 1964, pp. 241–252.
38. NIST/SEMATECH e-Handbook of Statistical Methods (online), https://www.itl.nist.gov/div898/handbook (accessed on 9 March 2023).
39. R Core Team, R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing, Austria, http://www.R-project.org/, 2023), (accessed on 9 March 2023).
40. Bartnik, A. The spatial distribution of low flows in Poland not exceeded at an assumed probability, Geographia Polonica 83(1), 2011. doi: 10.7163/GPol.2010.1.4.
41. Pyrce, R.S. Hydrological Low Flow Indices and their Uses. WSC Report No. 04. Watershed Science Centre, Peterborough, Ontario, 2004.
42. Fleig, A. Hydrological Drought – A comparative study using daily discharge series from around the world. MSc thesis (Diplomarbeit), Institut für Hydrologie, Albert-Ludwigs--Universität Freiburg, Germany, 2004.
43. Vladimirov, A.M. Stok rek v malovodiy period goda. Gidrometeoizdat, Leningrad, 1976.
44. Barbarossa, V.; Huijbregts, M.; Beusen, A.; Beck, H.E.; King, H.; Schipper, A.M. FLO1K, global maps of mean, maximum and minimum annual streamflow at 1 km resolution from 1960 through 2015. Sci Data 5, 180052, 2018, https://doi.org/10.1038/sdata.2018.52.
45. Linke, S.; Lehner, B.; Ouellet Dallaire, C. Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. Sci Data 6, 283, 2019. https://doi.org/10.1038/s41597-019-0300-6.
46. Beck, H.E.; van Dijk, A.I.J.M.; Miralles, D.G.; Richard, A.M.; de Jeu, L.A.; Bruijnzeel, S.; Mcvicar , T.R.; Schellekens, J. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. Water Resour. Res. 49, 2013, pp. 43–63.
47. Raczyński, K.; Dyer, J. Variability of Annual and Monthly Streamflow Droughts over the Southeastern United States. Water 14, 23: 3848, 2022. https://doi.org/10.3390/w14233848.
48. Baran-Gurgul, K.; Kołodziejczyk, K.; Rutkowska, A. Temporal and spatial variability of the mean river flow in Poland, regional approach [in:] Więzik B. (eds.) Współczesne problemy gospodarowania zasobami wodnymi: IV Krajowy Kongres Hydrologiczny, 21–23.09.2022, Warszawa, Komitet Gospodarki Wodnej Polskiej Akademii Nauk, Monografie Komitetu Gospodarki Wodnej PAN, 45, 2022, pp. 5–18 (in Polish).