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The spatial and temporal variability of hydrological drought in the Polish Carpathians

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Abstract: The aim of the study was to evaluate the climate and geographic factors controlling the hydrological drought of the rivers located in the Upper Vistula catchment in the Polish Carpathians. Drought was identified based on the daily flow (based on water stage measered once a day at 6 UTC) series dating from between 1975 and 2019 at 49 gauging cross-sections. Four physico-geographical regions were identified in the Polish Carpathians and spatial variabilities of the basic drought characteristics were developed within these regions. Such spatial distributions were treated as maps indicating drought hazard areas in the region. In addition, an analysis was undertaken to study the seasonality of the start and end times of the drought (all in the multi-annual period), the longest duration of droughts, the droughts of the highest volume in multi-annual period, as well as the number of drought days. Multi-annual variability of the number of drought days was also analysed.

The results suggest that droughts in the Polish Carpathians are events characteristic of summer and autumn, whereas in the Tatra Mountains and the Podhale region - of autumn and winter. The greatest hazard of a prolonged and high-volume drought occurs in the Podhale region and the Tatra Mountains, while the lowest hazard is observed in the Bieszczady Mountains and the eastern part of the studied area.

Keywords: Hydrological drought; Long-term variability; Seasonal variability; Vistula, the Polish Carpathian; Drought hazard.

INTRODUCTION

Extreme weather events, including floods and droughts, are characteristic of climate in Poland. Drought in Poland have been reported since the 14th century. Recently, climate change has been widely discussed in the literature. According to the study by Lorenc et al. (2008), performed on the data from the period between 1951 and 2006, the drought frequency in Poland increased in the last 25 years of the period in question. Wójcik et al. (2018) observed that in the last decade (after 2010) considerable droughts occurred, including agricultural drought.

Between 1951 and 2020, in Poland the average annual temperature was recorded to have increased by approximately 0.29 °C per decade (IMWM-NRI, 2021). Additionally, across the majority of Poland, a decline in the number of days with frost (with a maximum daily temperature below 0°C) and with severe frost (maximum daily temperature not higher than -10°C) has been observed (Ministry of the Environment, 2013).

In general, drought is a natural characteristic of climate, defined as a noticeable deficit of water in an environment, which results in damage to the environment and economy, and becomes a nuisance or even a hazard to a population (Hisdal and Tallaksen, 2000; Wilhite, 2005). Drought is a complex phenomenon which escapes a fully objective definition, therefore researchers from different fields describe it in varying ways. For geophysicists, its character is related to climate, meteorology, hydrology, limnology, glaciology, or it may refer to some aspects of soil physics (Yevjevich, 1967). For farmers, however, drought is inseparable with the water needs of various crops, whereas in the context of the economy, it is related to human activity and its underlying issues. Most often, drought is defined as a space-time process encompassing the following stages: atmospheric (meteorological) drought, soil (agriculture) drought, hydrological drought and, possibly, socio-economic drought (Mishra and Singh, 2010; Wilhite and Glanz, 1987). This work deals with the phenomenon of hydrological drought. The hydrological drought is most commonly defined as a continuous period during which streamflow at a given gauging station is below the assumed threshold value (threshold level) (Hisdal at al., 2001; Jakubowski, 2015; Ozga-Zielińska and Brzeziński, 1997; Smakhtin, 2001; Sutanto and van Lanen, 2021; Tallaksen and van Lanen, 2004; Tallaksen and van Lanen, 2007). The definition of drought as a threshold level method was introduced by Zielińska (1963) in Poland and by Yevjevich (1967) in the US.

The threshold level is most often percentile $Q_{p\%}$ read from the flow duration curve. The value of $Q_{p\%}$ is exceeded $p\%$ of time of observation. As such, the value of p may be interpreted as the average probability that a given (usually) daily stream flow is exceeded in an arbitrary year. The adopted values $Q_{p\%}$ as threshold value varies according to author are usually: $Q_{70\%}$ (Fleig, 2004; Fleig at al., 2006; Hisdal at al., 2001; Jakubowski, 2011; Stahl, 2001; Tallaksen and van Lanen, 2004; Tokarczyk, 2010, 2013; Tomaszewski, 2012), $Q_{90\%}$ (Fleig, 2004; Fleig at al., 2006; Gustard and Demuth, 2008; Hisdal and Tallaksen, 2000; Parry at al., 2012; Smakhtin, 2001; Stahl, 2001; Tallaksen and Hisdal, 1997; Tomaszewski, 2012; Zelenhasić and Salvai, 1987) and $Q_{95\%}$ (Fleig, 2004; Zelenhasić and Salvai, 1987).

In their research, many Polish authors (Ozga-Zielińska and Brzeziński, 1997; Tomaszewski, 2007; Zielińska, 1963) assume for threshold level the *WNQ* (maximum annual minimum flow) or *SNQ* (average annual minimum flow). Węglarczyk (2014) demonstrated that in the Upper Vistula catchment studied in this work, flow *SNQ* is approximately equal to $Q_{95\%}$, and *WNQ* to $Q_{76\%}$.

Considering the large spatial character of droughts, different authors have advised researching them in a regional context

(Tallaksen, 2000) as the results of individual case studies might not be comparable (Demuth and Stahl, 2001). This approach was used by, for example, Espinosa et al. (2019) in the study of atmospheric droughts on Madeira.

In Poland, the areas most susceptible to droughts, mainly hydrological droughts, are the catchments located in the region of the Central Poland Lowlands (Tokarczyk, 2010; Tomaszewski, 2012). Regardless of the location of the studied station, in order to assess the water resources of a catchment, it is necessary to analyse the seasonal and multi-annual flow variability (including low flows) and study the impact of the climate change on these resources. Such analyses are important to effective water management.

Carpathian rivers, however, as with most mountain rivers, are characterised by high slopes which cause high variability of the natural flow of water, as well as the volume and velocity of runoff. In the mountains, heavy rainfalls which cause a sudden increase in river flow are observed. At the same time, a low-permeable or non-permeable flysch sub-surface combined with decreased evaporation in mountainous areas (resulting from the air temperature being lower compared to other parts of the country) as well as frequent deforestation enables fast runoff (Ziemońska, 1973). Intense precipitation often causes high water levels in the summer. In contrast, large amounts of snow and long periods of snow cover contribute to the formation of deep and long-lasting winter drought, particularly characteristic of high-altitude areas. Small subsurface retention is responsible for the droughts occurring during other seasons, for example, in the autumn in mid-mountain and foothill areas. In the event of no precipitation, droughts may occur in the summer.

The aim of this study was to evaluate the climate and geographic factors controlling the hydrological drought of the rivers in the Polish Carpathians. To achieve the goal, spatial variability of the basic characteristics of a drought period was analysed, specifically the number of drought occurence N, mean drought duration T_{mean}, mean drought volume V_{mean}, as well as the longest drought T_{max} at a given cross-section and a drought of the highest deficit volume V_{max} (at a particular cross-section). Such spatial distributions may be utilised as maps indicating drought hazard areas in the studied region. Additionally, an analysis was done to study the seasonality of the start and end times of the drought (all in a multi-annual period), the T_{max} and V_{max} drought, as well as the number of days when the drought periods occurred. The multi-annual variability of the number of drought days was also analysed.

MATERIALS

Study area

The Carpathian Mountains in Poland stretch over the Upper Vistula catchment. Following the proposal of regionalisation by Solon et al. (2018), the following four physico-geographical regions were identified in the studied area: Western and Middle Beskidy Foothills, Western and Middle Beskidy Mountains, Central Western Carpathians, and Lesiste Beskidy Mountains (Fig. 1). In order to improve the legibility of the figures presented further in the paper, region I will be referred to as Beskidy Foothills, region II – Beskidy Mts., region III – Podhale and Tatra Mts. and region IV – Bieszczady Mts. (Table 1).

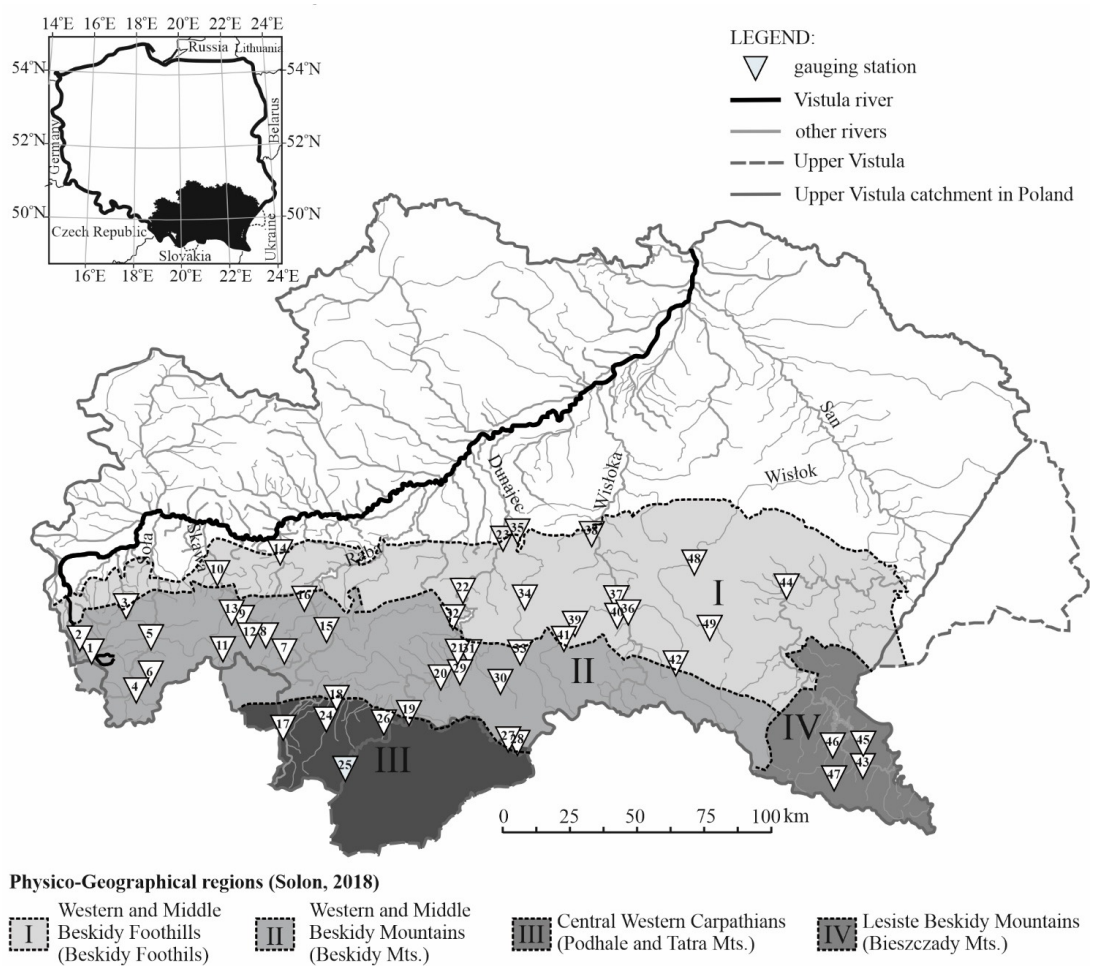


Fig. 1. Study area and location of selected gauging stations.

Table 1. Climate and geography characteristics of the selected physico-geographical regions.

Physico-geographical region		Geomorphology and geological structure [1)]	Climate [2)]	H [3)] (mm)	t [4)] (°C)	P [5)] (mm)
I	Beskidy Foothils	The Carpathian Foothills is an upland area in Outer Western Carpathians with height differences of 80–250 m, whose smooth plateaus cut the tectonic structures of the Carpathian flysch. This flysch consists mainly of sedimentary rocks, mainly of conglomerates, sandstones, mudstones and clay stones.	The climate is moderately warm, sub-mountainous.	700–900	7–8	450–500
II	Beskidy Mts.	The Beskidy mountain range (in Outer Western Carpathians), includes medium and low mountains with steep slopes (a gradient often greater than 20 degrees). The ridges of the low mountains lie at an altitude of 300–350 m above the valley floors, and the ridges of the middle mountains - at 400-800 m. The Beskids are made of Carpathian flysch.	The climate is mountainous, air temperature changes with height (average fall is 0.6 ° C at 100 meters). In the Bieszczady Mts., the influence of the continental climate is noticeable. In Podhale and the Tatra Mts., periodic occurrence of dry and warm mountain winds, causing a rapid rise in air temperature, is characteristic.	850–950 (central and eastern part), up to 1400 (weastern part)	6–7	400–500
III	Podhale	Podhale (part of Central Western Carpathians) is a vast tectonic depression between the Tatra Mountains and the Beskids. It is made of Podhale flysch (a variety of Carpathian flysch). Podhale is characterized by a belt-shaped relief pattern; : going from the foreland of the Tatra Mountains towards the north, the following subregions can be distinguished: Podtatrzański Trench (800–900 m a.s.l.), Gubałowskie Foothils (800–1000 m a.s.l.), Pieniny Klippen Belt (700-800 m a.s.l.) and Orawsko-Nowotarska Basin.		800–1000	4–5	400–450
	Tatra Mts.	Tatra Mts. (part of Central Western Carpathians) have a typical alpine-denudation and karst relief sculpture. They are made of crystalline rocks (granites, metamorphic rocks) and sedimentary rocks (limestones, dolomites, sandstones, etc.). The highest peak in the Polish Tatra Mts. is Rysy - 2499 m a.s.l.		above 1000, in the highest parts of the mountains: 1500–1650	2–4, in the high parts of the mountains to –4	less than 400
IV	Bieszczady Mts.	The Bieszczady Mts. (Outer Eastern Carpathians) have the features of grate mountains built of Carpathian flysch. The ridges are mostly made of hard sandstones, while in the valleys soft slates predominate. The sculpture of the Bieszczady Mountains is mainly denudative. The ridges are clearly rising to the east: from 900 to 1,300 m a.s.l. (the highest peak is Tarnica 1,349 m a.s.l.).		1000–1300	4–5	less than 400

H – annual precipitation, t - average annual temperature, P - mean annual evaporation
Sources: [1,3)] Kostrzewski at al. (2021), Klimaszewski (1972) [2,5)] Niedźwiedź and Obrębska-Starklowa (1991), [3)] Jokiel at al. (2017)

In the studied area, Niedźwiedź and Obrębska-Starklowa (1991) identified the Carpathian Foothills region (encompassing regions I) and mountain climate region (regions II, III and IV). The mountain climate region is abundant in precipitation and the altitude affects climate, varying between its altitudinal layers. On the border with the Beskidy Mountains, average annual temperature is approximately 7 °C and the annual precipitation total is approximately 900 mm. As altitude increases, the temperature decreases, and the annual precipitation total increases. The Carpathian Foothills region is characterised by a moderate warm climate, with an average annual temperature of 7–8 °C and damp climate (annual precipitation total is between 700 and 900 mm). The geomorphic and geological structure is described in Table 1.

Data

The data utilised in this study was obtained from the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI) in form of daily (which based on water stage measered once a day at 6 UTC) series from the period between 01 Nov 1974 and 31 Oct 2019 (which yields a total of 45 hydrological years). The time series were obtained from 49 gauging cross-sections located in the Polish Carpathians (Fig. 1).

Almost all of the studied catchments (47 out of 49) have areas below 3,000 km^2, and nearly half of these areas (23 out of 49) is smaller than 300 km^2 (Fig. 2a). The largest catchments within the studied area have areas of over 5,000 km^2 and are enclosed by Czchów (cross-section No. 22) and Zgłobice (cross-section No. 23) on the Dunajec River (Fig. 1, Table 2).

Over half of the gauging stations (30 out of 49) are located at altitudes below 400 m a.s.l. (Fig. 2, Table 2). Due to the landscape becoming higher in the southern direction, the stations located at the lowest altitudes (below 315 m a.s.l.) are in the regions of the Beskidy Foothills and the northern part of the Beskidy Mountains, whereas the stations located at the highest altitudes (above 600 m a.s.l) are those in the catchment of the Upper Dunajec, in the region of Podhale and the Tatra Mountains. (Białka River/Łysa Polana – 25, Czarny Dunajec River/Koniówka – 17 and Biały Dunajec River/Szaflary – 24) (Fig. 1). The stations within the Bieszczady Mountains region are located at altitudes between 430 and 575 m a.s.l.

The mean specific flow $\overline{q}$ in the studied area has values between approximately 9 dm^3 s^{-1} km^2 and 50 dm^3 s^{-1} km^2. Those flows increase with altitude (Fig. 2), therefore the lowest values are observed in highlands, while the highest - in the mountains. Without a doubt, the highest flow can be observed at a cross-section located at the highest altitude, Łysa Polana (25) of the Białka River.

Table 2. Characteristics of gauging cross-sections and catchments enclosed by those sections (Czarnecka, 2005), and mean flow Q_{mean} in the 45-year period (1975–2019).

No	River	Cross-section	Latitude (N)	Longtitude (E)	Cachment area (km^2)	Gauging stations elevation (m a.s.l)	Physico-geographical region	Q_{mean} (m^3/s)
1	Vistula	Wisła	49°37′55″	18°54′03″	53.6	470.6	Beskidy Mts.	1.3
2	Vistula	Ustroń-Obłaziec	49°40′50″	18°51′01″	107.4	398.7	Beskidy Mts.	2.6
3	Biała	Mikuszowice	49°46′46″	19°04′27″	32.6	360.9	Beskidy Mts.	0.6
4	Soła	Rajcza	49°30′50″	19°06′59″	253.8	482.0	Beskidy Mts.	5.2
5	Soła	Żywiec	49°41′11″	19°11′36″	782.8	342.0	Beskidy Mts.	16.0
6	Żabniczanka	Żabnica	49°33′53″	19°10′49″	23.9	564.8	Beskidy Mts.	0.7
7	Skawa	Jordanów	49°38′11″	19°49′48″	96.8	442.9	Beskidy Mts.	1.2
8	Skawa	Osielec	49°41′01″	19°44′21″	243.6	393.6	Beskidy Mts.	3.7
9	Skawa	Sucha Beskidzka	49°44′22″	19°36′31″	466.1	324.0	Beskidy Mts.	6.8
10	Skawa	Wadowice	49°52′38″	19°30′40″	833.4	254.1	Beskidy Foothils	12.6
11	Skawica	Zawoja	49°38′26″	19°32′07″	46.1	577.5	Beskidy Mts.	1.3
12	Skawica	Skawica Dolna	49°41′10″	19°39′49″	135.7	408.0	Beskidy Mts.	3.3
13	Stryszawka	Sucha Beskidzka	49°44′36″	19°36′04″	140.5	323.9	Beskidy Mts.	3.6
14	Skawinka	Radziszów	49°56′24″	19°48′32″	318.1	213.5	Beskidy Foothils	3.0
15	Raba	Kasinka Mała	49°42′17″	20°01′57″	353.3	356.9	Beskidy Mts.	5.7
16	Raba	Stróża	49°47′49″	19°55′29″	644.2	297.0	Beskidy Mts.	10.2
17	Dunajec	Koniówka	49°23′44″	19°49′05″	132.8	725.8	Podhale and Tatra Mts.	4.4
18	Dunajec	Nowy Targ-Kowaniec	49°29′13″	20°03′13″	686.9	573.5	Podhale and Tatra Mts.	14.6
19	Dunajec	Krościenko	49°26′30″	20°25′46″	1580.0	413.5	Podhale and Tatra Mts.	32.5
20	Dunajec	Gołkowice	49°33′01″	20°34′13″	2039.8	311.9	Beskidy Mts.	39.4
21	Łubinka	Nowy Sącz	49°38′07″	20°42′17″	66.6	281.3	Beskidy Mts.	0.66
22	Dunajec	Czchów	49°48′59″	20°40′55″	5317.3	222.4	Beskidy Foothils	72.2
23	Dunajec	Zgłobice	49°58′30″	20°52′47″	5647.5	189.6	Beskidy Foothils	78.2
24	Biały Dunajec	Szaflary	49°25′27″	20°01′29″	209.9	635.5	Podhale and Tatra Mts.	5.3
25	Białka	Łysa Polana	49°15′49″	20°06′54″	63.4	965.6	Podhale and Tatra Mts.	3.2
26	Niedziczanka	Niedzica	49°24′41″	20°18′08″	136.7	495.7	Podhale and Tatra Mts.	2.1
27	Poprad	Muszyna	49°20′22″	20°53′31″	1518.8	446.3	Podhale and Tatra Mts	17.9
28	Poprad	Muszyna-Milik	49°21′00″	20°53′07″	1700.4	440.4	Podhale and Tatra Mts	20.7
29	Poprad	Stary Sącz	49°34′07″	20°39′35″	2075.0	295.3	Beskidy Mts.	25.5
30	Kamienica	Łabowa	49°31′35″	20°51′32″	64.9	450.2	Beskidy Mts.	1.1
31	Kamienica	Nowy Sącz	49°37′31″	20°41′45″	237.0	278.8	Beskidy Mts.	3.0
32	Łososina	Jakubkowice	49°44′22″	20°37′48″	347.1	246.3	Beskidy Foothils	4.6
33	Biała	Grybów	49°37′26″	20°56′45″	207.0	320.5	Beskidy Mts.	2.8
34	Biała	Ciężkowice	49°47′32″	20°58′25″	524.6	238.5	Beskidy Foothils	5.8
35	Biała	Koszyce Wielkie	49°59′50″	20°56′58″	955.0	189.7	Beskidy Foothils	9.3
36	Wisłoka	Żółków	49°43′48″	21°27′33″	582.0	224.9	Beskidy Foothils	7.5
37	Wisłoka	Krajowice	49°46′20″	21°24′45″	2095.4	213.4	Beskidy Foothils	24.3
38	Wisłoka	Łabuzie	49°59′16″	21°18′35″	2552.7	184.7	Beskidy Foothils	28.0
39	Ropa	Klęczany	49°42′05″	21°13′00″	484.1	259.1	Beskidy Foothils	6.4
40	Ropa	Topoliny	49°43′29″	21°26′36″	974.2	224.8	Beskidy Foothils	10.5
41	Sękówka	Gorlice	49°39′17″	21°10′13″	122.5	279.2	Beskidy Foothils	1.8
42	Jasiołka	Zboiska	49°34′28″	21°41′54″	264.3	311.6	Beskidy Foothils	3.7
43	San	Zatwarnica	49°14′06″	22°33′47″	494.2	486.2	Bieszczady Mts.	11.5
44	San	Dynów	49°48′03″	22°14′39″	2944.9	234.8	Beskidy Mts.	46.4
45	Czarna	Polana	49°18′09″	22°34′27″	94.1	437.4	Bieszczady Mts.	1.6
46	Solinka	Terka	49°17′59″	22°25′45″	309.1	432.8	Bieszczady Mts.	8.3
47	Wetlina	Kalnica	49°11′20″	22°25′45″	119.0	573.7	Bieszczady Mts.	3.6
48	Wisłok	Żarnowa	49°52′40″	21°49′03″	1433.0	213.5	Beskidy Foothils	13.5
49	Morwawa	Iskrzynia	49°40′38″	21°51′51″	107.4	266.3	Beskidy Foothils	1.3

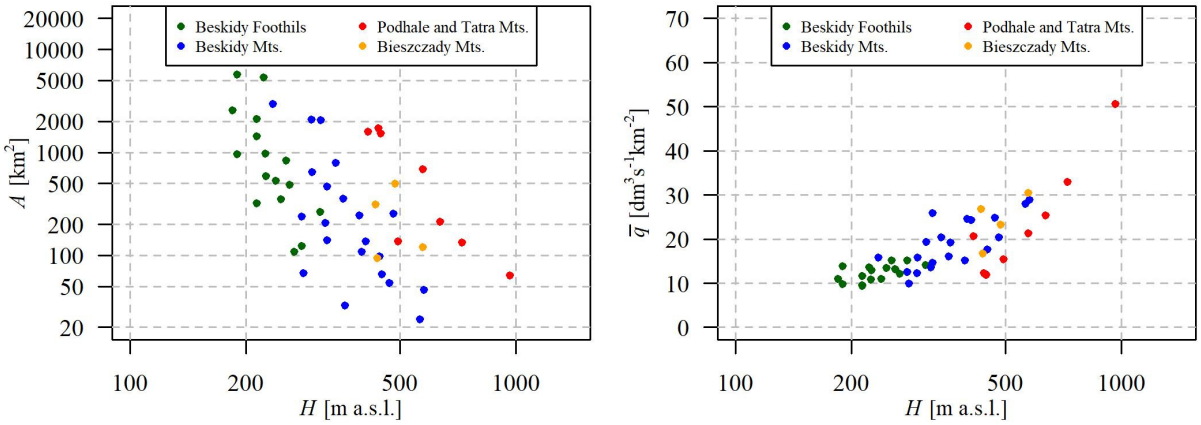


Fig. 2. Correlations between catchment area A enclosed by a gauging cross-section and mean specific flow $\overline{q}$, and the gauging stations elevations H, for 49 gauging cross-sections in the Polish Carpathians.

METHODS

Definition of drought

A drought period is most commonly defined by one of the three methods: *POT* (Peak Over Threshold), *MA* (Moving Average) or *SPA* (Sequent Peak Algorithm) (Fleig, 2004). For the purposes of this study, the *POT* method was used, which in its basic form defines a drought as a period during which a flow remains below the value of Q_g, and the end of the drought occurs when flow once again is equal to or exceeds the value of Q_g (Tallaksen and van Lanen, 2007; Tokarczyk, 2010).

Based on a multi-annual daily flow series Q_t at a given gauging cross-section, time series $t_{p,i}$ and $t_{k,i}$ are created which indicate the start and end time of a drought (i = 1, 2…), thus helping define different drought characteristics:

– the duration T_i of drought i:

$$T_i = t_{k,i} - t_{p,i} + 1 \text{ [day]} \tag{1}$$

– the volume of drought V_i (shortage or deficit volume):

$$V_i = \sum_{i=t_{p,i}}^{t_{k,i}} \left(Q_g - Q_i\right) / \overline{Q} \text{ [day]} \tag{2}$$

where $\overline{Q}$ is a mean daily flow from a multi-annual period.

Measuring the volume of a drought in days (2) shows the number of days needed to fill up a drought with mean flow at a given cross-section, which allows for the comparison of volumes at various gauging cross-sections.

Owing to the fact that a short, few-days-long period (minor drought) with flow below Q_g may not be considered significant in terms of water shortages, an additional assumption of a minimum drought duration t_{min} is employed in order to identify the drought duration. In literature, the value t_{min} ranges widely from five to as much as 20 days - most commonly being five or seven days (Jakubowski, 2011; Tallaksen and van Lanen, 2004; Tokarczyk, 2010; Zelenhasić and Salvai, 1987).

Fleig at al. (2006), Tallaksen at al. (1997) and Zielińska (1963) state that if the time between the adjacent drought periods is very short, then such droughts may be considered dependent (as they have the same cause) and may be combined into one. The inter-event time criterion (IT) was introduced by Zelenhasic and Salvai (1987). According to this criterion, if two adjacent droughts durations T_i and T_{i+1} and volumes V_i and V_{i+1} are separated by a time distance τ_i shorter than the threshold value τ_{max}, then they can be combined into one drought of increased duration T_i' and volume V_i':

$$T_{i'} = T_i + T_{i+1};\ V_{i'} = V_i + V_{i+1} \tag{3}$$

Most frequently, authors assume a value of τ between two to six days dni (Gustard and Demuth, 2008; Tallaksen at al., 1997; Tomaszewski, 2012; Jakubowski, 2011; Zelenhasić and Salvai, 1987).

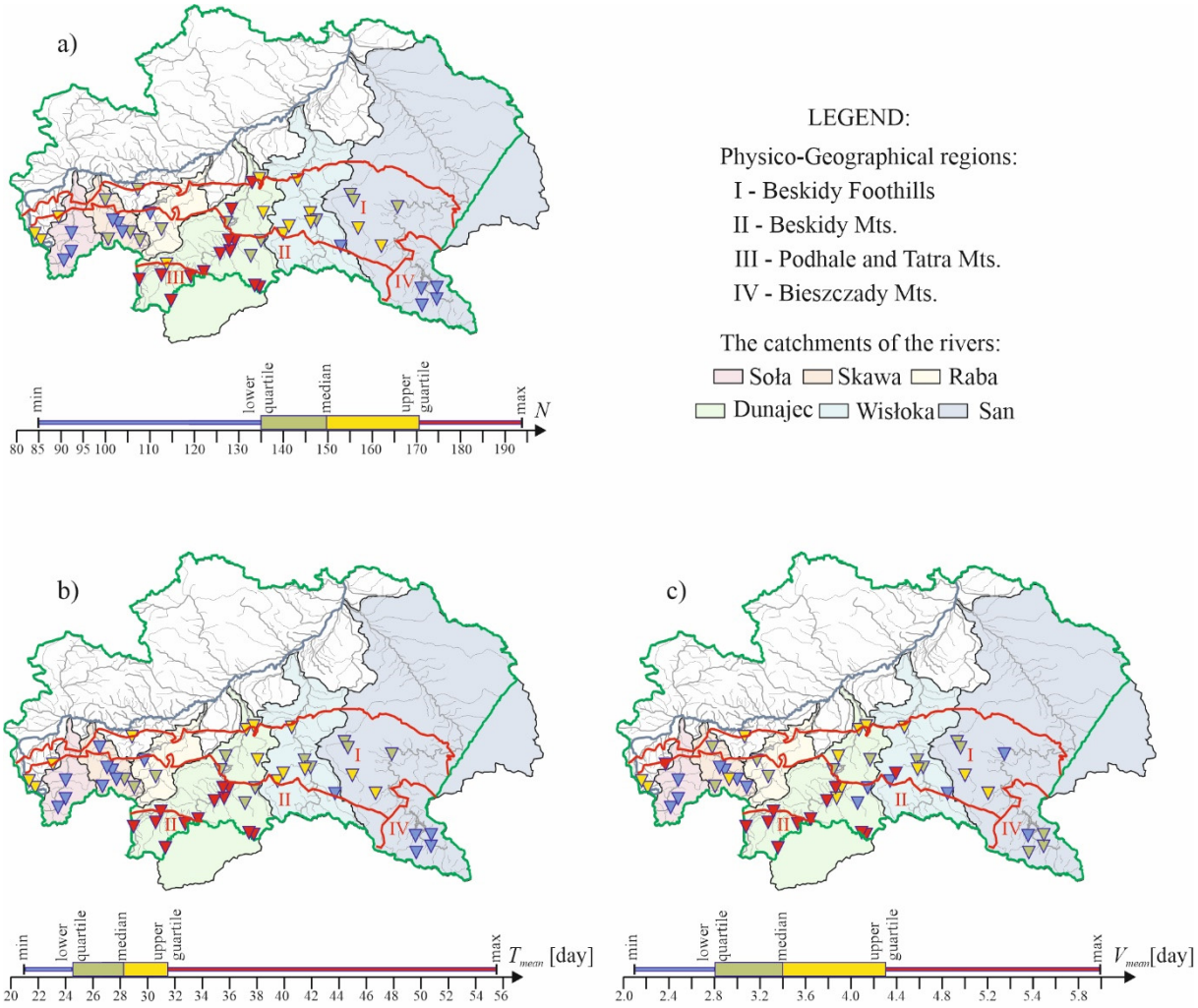
In this study, a drought period was defined as a sequence of streamflows lasting a minimum of seven days, with values equal to or below the threshold flow $Q_{70\%}$. Additionally, it was assumed that in the event of the time between the adjacent droughts being shorter than three days, they could be considered to have the same cause (being dependent) and they were combined.

Further scope of the study includes:

- an analysis of spatial variability of the basic characteristics of a drought period, specifically the number of droughts N, mean drought duration T_{mean}, mean drought volume V_{mean},
- an analysis of spatial variability of the longest drought T_{max} and a drought of the highest volume V_{max} in a multi-annual period,
- an analysis of the seasonality of the start and end times of the droughts (all in a multi-annual period), as well as the T_{max} and V_{max} drought periods, an analysis of the drought days including the seasonality of the start and end times N_d, and the multi-annual variability N_d.

The calculated values of the droughts N, the mean duration T_{mean}, the mean volume V_{mean}, the longest duration T_{max} and the highest volume V_{max} overlaid separately on the map of the studied area produce a spatial picture of the variability of these characteristics and depict the scale of the drought period hazard.

A hazard is understood here as a value growing with N, T_{mean}, V_{mean}, T_{max} and V_{max}. In order to be able to compare these maps, the value ranges of the individual characteristics were divided into categories using the quartiles of these characteristics as threshold class values. Such classification enables qualitative comparison of the variability of different variables, especially when their values differ significantly. The coding utilised is shown in table in Fig. 3. The obtained maps, including the values of the particular quartiles, are shown in Fig. 3.



Category	Colour assigned to category	Drought hazard	Number of drought N	Mean drought duration T_{mean}	Mean drought volume V_{mean}
$[X_{min}, X_{25\%}]$		low	low	low	low
$(X_{25\%}, X_{50\%}]$		moderate	moderate	moderate	moderate
$(X_{50\%}, X_{75\%}]$		high	high	high	high
$(X_{75\%}, X_{100\%}]$		very high	very high	very high	very high

Fig. 3. Spatial distribution of: a) the number of drought periods N, b) mean duration T_{mean}, c) mean volume V_{mean}, according to the quartile classification, including the box and whisker plots in the multi-annual hydrological period between 1975 and 2019. The table contains colour- and language-coding in the quartile classification of the droughts characteristics.

Trend analysis

In order to identify potential monotonic trends in the drought characteristics series, authors utilised the non-parametric Mann-Kendall test (Kendall, 1975; Mann, 1945) with the statistical significance α equal to 0.001 (strong trends) and 0.05 (average trends).

The statistics of the Mann-Kendall test for monotonic trend were calculated according to (Hamed and Rao, 1998; Kendall, 1975; Mann, 1945):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{4}$$

where:

$$\operatorname{sgn}(x) = \begin{cases} \mathbf{1} & \text{if } x > \mathbf{0} \\ \mathbf{0} & \text{if } x = \mathbf{0} \\ \mathbf{-1} & \text{if } x < \mathbf{0} \end{cases} \tag{5}$$

When H0: S = 0 is true, the mean is E(S) = 0 and variance of S (including the correction term for ties) are given by:

$$\operatorname{var}(S) = \frac{n(n-1)(2n+5)}{18} - \frac{\sum_{i=1}^{k} t_i \cdot i(i-1)(2i+5)}{18} \tag{6}$$

where k is the number of the tied groups in the data set and t_i is the number of data points in the i-th tied group. The statistic S is approximately normally distributed, with

$$Z = S / \sigma \tag{7}$$

The magnitude of trends was determined using Theil-Sen's slope (Helsel at al., 2020; Sen, 1968; Theil, 1950) defined as:

$$a = \text{median}\frac{y_j - y_i}{x_j - x_i}, \quad \text{for all } i < j, \quad i = 1, 2, ..., (n-1), j = 2, 3, ..., n, \tag{8}$$

All calculations, including he *p*-values of the Mann-Kendall test were obtained using the GNU R software (R Core Team, 2021).

RESULTS AND DISCUSSION

The basic characteristics of drought are its duration, volume, starting and ending times. There are also certain parameters which may be viewed over a longer time, such as the number of occurence droughts or the number of drought days in a multi-annual period or in its particular months.

Spatial distributions of the number of drought periods, mean drought duration and mean drought volume

Within the studied area, in the period between 1975 and 2019, at 49 gauging cross-sections, there were 152 drought events observed of mean duration 28.8 days and mean volume 3.6 days.

Mean duration T_{mean} and mean volume V_{mean} of a drought increase, while the number of drought N decreases with the altitude H of a given station. The values of the correlation coefficients $corr(H, T_{mean})$ and $corr(H, V_{mean})$ are not high, being 0.44 and 0.37, respectively. However, they are statistically significant at the significance level $\alpha = 5\%$.

All of the spatial distributions of the droughts N, the mean duration T_{mean} and the mean volume V_{mean} shown in Fig. 3 reveal more or less clear grouping of the gauging stations which belong to individual categories and some areal (catchment-regional) similarities and differences of drought characteristics. This grouping is distinctly similar on all three maps.

The most numerous concentration of drought hazards which belong to the "very high" category, specifically of sections with the longest drought periods (T_{mean} above 31.6 days) and the greatest volume (V_{mean} above 4.3 days) occurs in the Upper Dunajec (the region of Podhale and the Tatra Mts.) and in the Beskidy part of the Dunajec River catchment. These areas, at the same time, have a lower number of drought periods compared to the remainder of the studied area ($N < 135$).

Conversely, the lowest hazard occurs in the Bieszczady Mts. (the Upper San river catchment) where the mean drought duration is short (it belongs to the "low" category, $T_{mean} < 21.7$ days) and the mean drought volume is small (the "moderate" category, 2.8 days $< V_{mean} <$ 3.4 days or "low", $V_{mean} < 2.8$ days). Meanwhile, there were many drought events in this area (the "very high" category, the number of drought being above 171 in a multi-annual period).

A similar situation to the one occurring in the Bieszczady Mts. may be observed in the catchments of the rivers: Soła, Skawa and Raba, where T_{mean} and V_{mean} belong to the "high" or "very high" categories, while N – to the "low" or "moderate".

The drought hazard in the remaining part of the studied area, namely the Beskidy part of the catchments of the rivers: Small Vistula, Dunajec, Wisłok and San are most often "moderate" or "high".

The observations concerning the Bieszczady and Beskidy Mountains, and most importantly the Subcarpathians area, coincide with the study results by Tlałka (1982) who found that droughts in the Bieszczady Mts. and Beskidy Mts. are short, whereas their durations vary in the Beskidy Foothills area. The discrepancy of results between the Podhale and Tatra Mts. (where Tlałka identified the short droughts) may result from the fact that this author considered the summer droughts only, while long high-volume drought periods in this area occur during winter.

Spatial distributions of extreme drought periods

Drought periods do not occur every year and sometimes it is possible to observe a high number of short but shallow events. For this reason, many authors (Baran-Gurgul, 2018; Jakubowski, 2011) studied the most problematic or extreme ones, for example the maximum annual droughts. Extreme droughts in this study are considered: a drought T_{max} with the longest duration in a multi-annual period and a drought V_{max} with the largest volume duration in a multi-annual period. In the study area, in the years 1975–2019, in 49 water gauge sections, the longest observed droughts lasted from 105 to 235 days, and the largest drought volumes ranged from 14.5 days to 53.5 days.

Similar to the analysis of the number of drought days, mean drought duration and mean volume, where the spatial distributions N, T_{mean} and V_{mean} were created based on the quartile classification, the authors used the same method of categorisation for the T_{max} and V_{max} variables. The utilised colour-coding the derived maps are presented in Fig. 4.

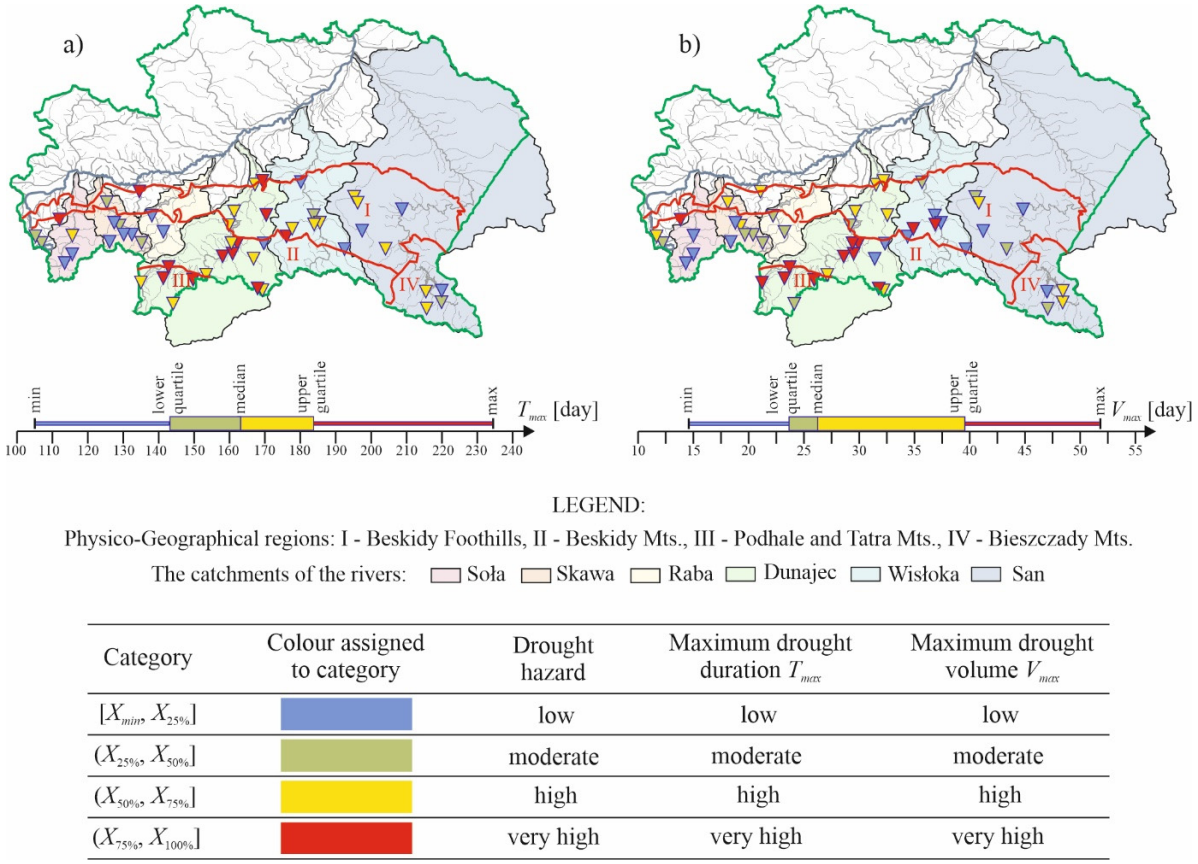
The greatest hazard of a drought with T_{max} longer than 184 days or volume V_{max} above 39.9 days occurring is in the Dunajec catchment as well as at some gauging cross-sections in the catchments of the Wisłoka River or Small Vistula (the upper part of the Vistula, the source to the tributary - Przemsza River). It is worth paying special attention to the following cross-sections: Krościenko (19) and Gołkowice (20) at the Dunajec River, as well as Klęczany (39) and Topoliny (40) at the Ropa River. These cross-sections are located within an area exposed to the reservoirs on the Dunajec River and Ropa River, where the T_{max} and V_{max} drought hazard are "high" or "very high".

In the catchment of the San River, both in its Beskid and Bieszczady parts, no clear grouping of catchments belonging to any particular categories is observed, and the T_{max} and V_{max} drought hazard is average (none of the cross-sections are exposed to the "very high" hazard category).

The hazard of a drought with the greatest volume and the longest duration in a multi-annual period occurring in the Beskidy Mts. catchments of the rivers: Soła, Skawa and Raba at the majority of the stations are "low" or "moderate".

Seasonality of the beginning and end time of a drought event

Fig. 5 presents the yearly distribution of the mean relative number of the drought beginnings t_{beg} and ends t_{end} in the multi-annual period in the studied area. As can be seen from this comparison, droughts in the Beskidy Mts., Beskidy Foothils and Bieszczady Mts. usually begin in July, August or September, and end in September or October. In the Podhale and Tatra Mts., hydrological droughts occur at a later time; the beginning of a drought usually occurs between September and January (the maximum distribution of t_{beg} is on January), whereas the end is observed between December and March (the maximum distribution of t_{end} falls in March).



Category	Colour assigned to category	Drought hazard	Maximum drought duration T_{max}	Maximum drought volume V_{max}
$[X_{min}, X_{25\%}]$		low	low	low
$(X_{25\%}, X_{50\%}]$		moderate	moderate	moderate
$(X_{50\%}, X_{75\%}]$		high	high	high
$(X_{75\%}, X_{100\%}]$		very high	very high	very high

Fig. 4. Spatial distribution of: a) the duration of the longest drought T_{max} and b) the largest drought volume V_{max}, according to the quartile classification, including the box and whisker plots in the hydrological period between 1975 and 2019. The table contains colour- and language-coding in the quartile classification of the drought T_{max} and V_{max} characteristics.

Droughts in the Beskidy Mts. and Bieszczady Mts. begin least frequently in March or April, and the minimum t_{end} in the Podhale and Tatra mts. falls in June.

There are number of cross-sections at which the drought starting and ending times distribution in a year is markedly different compared to other stations located within the same region. These cross-sections include the highest cross-section located in the whole study area (Łysa Polana (25) at Białka River in the Podhale and Tatra Mts. region), at which a drought usually ends in March or April (later than in the remaining part of the region).

Some deviations from the mean distribution in the year of t_{beg} and t_{end} may also be observed in the Beskidy Mts. region, where the droughts at Krościenko (19) and Gołkowice (20) sections of the Dunajec River or Łabowa (30) and Nowy Sącz (31) sections of the Kamienica river begin in December or January, and end in February or March.

Similar conclusions were reached by Ziemońska (1973), who studied water relations in the Polish Western Carpathians and their spatial variability within the period between 1951 and 1960. The author found that drought periods from the multi-annual period she had studied within the western part of the chosen area occurred in January and February, whereas in the eastern part - in September and November. The month with no observed droughts was April, and in the high mountain region - also May and June.

Seasonality of the number of days in a drought period

The annual distributions of the mean number of drought days N_d in the Beskidy Mts. and Bieszczady Mts. are similar. The droughts typically occur in the summer and autumn, while in the Podhale and Tatra Mts. they often occur later, in the autumn-winter time (Fig. 6). The most drought days N_d in the Beskidy Mts. and Bieszczady Mts. fall on the months between August and October, whereas the lowest values of N_d are observed in April (Fig. 6). In Podhale and the Tatra Mts., drought periods occur later, with most of the drought days falling on the period between November and February, and the minimum N_d occurs in May.

The annual distribution of N_d in Podhale and the Tatra Mts. has a significantly different N_d distribution for one of the gauging stations. More specifically, it is the annual distribution N_D for Łysa Polana of the Białka river, the highest-located station within the whole area. At this station, droughts occur primarily in the winter, while the highest number of drought days occur between January and March.

Maximum drought periods - in a year and a multi-annual period

The longest observed droughts in the multi-annual period do not always have the highest volume, therefore the drought period duration T_{max} does not always overlap with the time of V_{max} (Fig. 7). The longest droughts in the period between 1975 and 2019 which were registered at the highest number of cross-sections were observed for 2003 (at 12 out of 49 gauging cross-sections), 1986 (at 11) and 2015 (at 8). These drought periods were characterised by high volume, often being the maximum multi-annual value V_{max}.

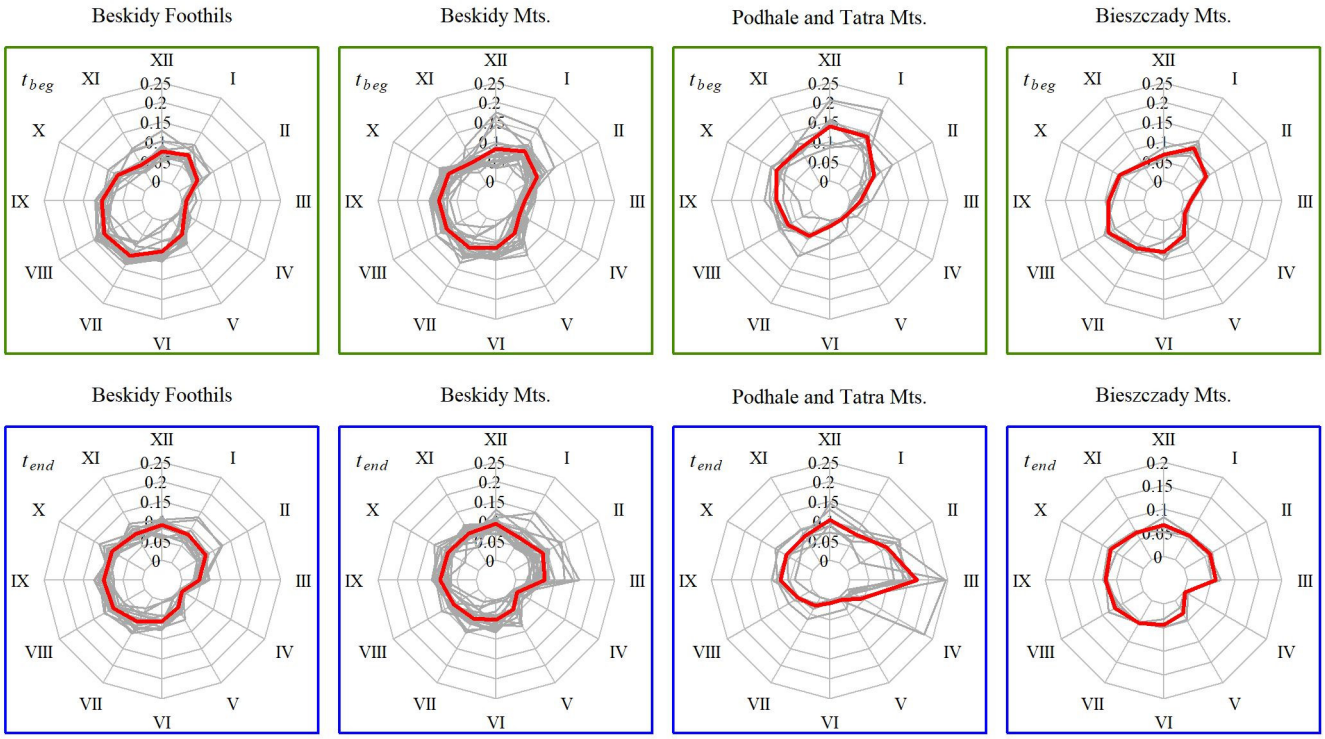


Fig. 5. Distribution in the year of the mean relative number of the drought beginning t_{beg} and end t_{end} in the studied area. The relative areal mean values are marked in red.

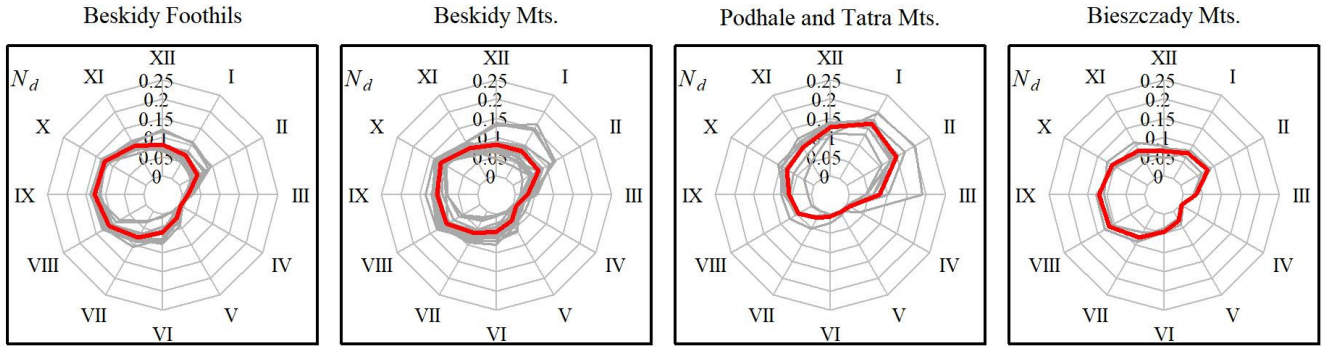


Fig. 6. Annual distribution of the mean number of drought days N_d at a given station in the studied area. The relative areal mean values are marked in red.

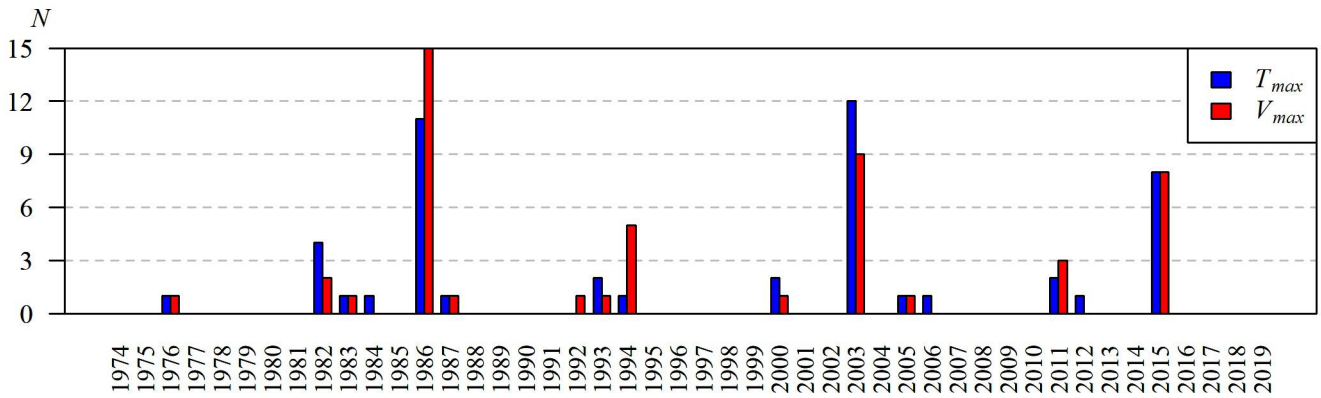


Fig. 7. Distribution of the maximum T_{max} and V_{max} drought, at 49 gauging cross-sections N in the Polish Carpathians between 1975 and 2019.

Table 3. Characteristics of the drought T_{max} and V_{max}.

Region	Years with the most frequently occurring middles of drought periods T_{max} i V_{max}	Beginning time of the droughts T_{max} i V_{max}	Ending time of the droughts T_{max} i V_{max}	Mean regional drought duration T_{max}	Mean regional drought volume V_{max}
I	1982, 1986, 2003, 2015	VI – IX	XI – II	172 days	29.7 days
II	2003, 2015	VI – IX	XI – II	156 days	27.7 days
III	1986-87, 2003	VIII – X	II – III	182 days	40.9 days
IV	1986	VI – IX	XI – II	158 days	27.5 days

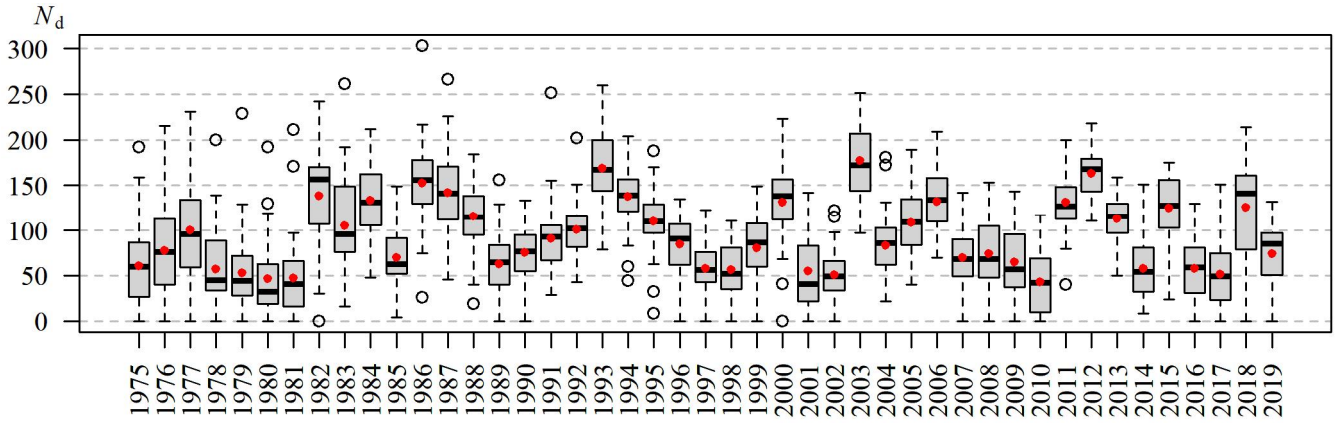


Fig. 8. Distribution of the drought days N_d in Polish Carpathians in the period between 1975 and 2019. Horizontal lines in bold refer to medians, and the red points to mean values.

The droughts observed in 2003 and 2015 in the study area extended to all of Poland and also the area of Slovakia (Fendeková et al., 2018).

Spinoni et al. (2019), who analysed 4,500 drought events at a global scale, in the period between 1951 and 2016 in Europe and identified the 52 biggest droughts, highlighted the unprecedented drought event which was the result of the 2003 heatwave.

On the other hand, the World Meteorological Organisation (WMO, 2016) confirmed that 2015 was the warmest year on record since 1961. Boczoń et al. (2016) and Staśko and Buczyński (2018) also paid attention to the hydrological drought which occurred in 2015, whereas Krasowski and Tokarczyk (2017), included it in the long-term and severe categories when comparing the drought periods from the multi-annual period. The hydrological drought that occurred in 2015 in southern Poland was also noted by Laaha et al. (2017).

In the mountains (the Podhale and Tatra Mts. as well as the Bieszczady Mts.), between 1975 and 2019, the T_{max} and V_{max} droughts occurred predominantly in 1986 (Bieszczady Mts.) and in 1986–1987, and 2003 (Tatra Mts.). This coincides with the observations made by Vido et al. (2015), Antofie et al. (2015) and Spinoni et al. (2013), who also treated those years as dry against the multi-annual period in this area.

Mean regional durations T_{max} and mean regional volumes V_{max} have the highest values in the Podhale and Tatra Mts. regions. Slightly lower are in the Beskid Foothills, and the lowest occur in the Bieszczady Mts. and Beskid Mts. (Table 3).

The longest maximum drought periods usually begin in the Beskid Mts. or Bieszczady Mts., between June and September, and end between November and February. In the Tatra Mts., these drought periods are observed later; the starting time of a maximum drought is usually around August to October, and the ending around February or March.

Multi-annual variability of the days with a drought

The number of drought days refers to the number of days in a given hydrological year in which a drought period occurred (with intervals). It should be highlighted that a year with the longest drought period in a multi-annual period may be, though it frequently is not, the year in which the greatest number of drought days was observed. Firstly, if a maximum drought begins during one and ended during the subsequent year, then it is not divided evenly but it is included in the year when its middle occurred. Secondly, it is common to observe many short droughts in a given year rather than one of a significant duration.

The highest number of drought days (N_d equal to 229 days) at Wadowice (10) cross-section of the Skawa River was observed in 1993, while the longest drought at this section, between 1975 and 2019 was assigned to 2015. This maximum drought period lasted for 149 days - between 21 June and 16 November 2015.

However, as mentioned above, 2003 was very dry, therefore the mean areal number of days with a drought N_d was indeed the highest in 2003 (Fig. 8). The following years with high mean areal number of drought days (above 150 days) were (according to N_d): 1993, 2012, 1986 and 1987.

The time series of the number of drought days N_d at the studied 49 gauging cross-sections were analysed using the Mann-Kendall trend test. The p_v values of the hypothesis test in all of the analysed cases are shown in Fig. 9. A statistically significant trend was identified in ten out of 49 drought days series. The majority (seven out of ten) are upward trends, probably resulting from climate warming. The remaining three are downward trends, which is most likely the result of the functioning reservoirs on the Ropa River and Dunajec River, which were approved for use during the time of the study. Cross-section Klęczany is located on the Ropa River, below the reservoir Klimkówka (39), which was opened for use in 1994;

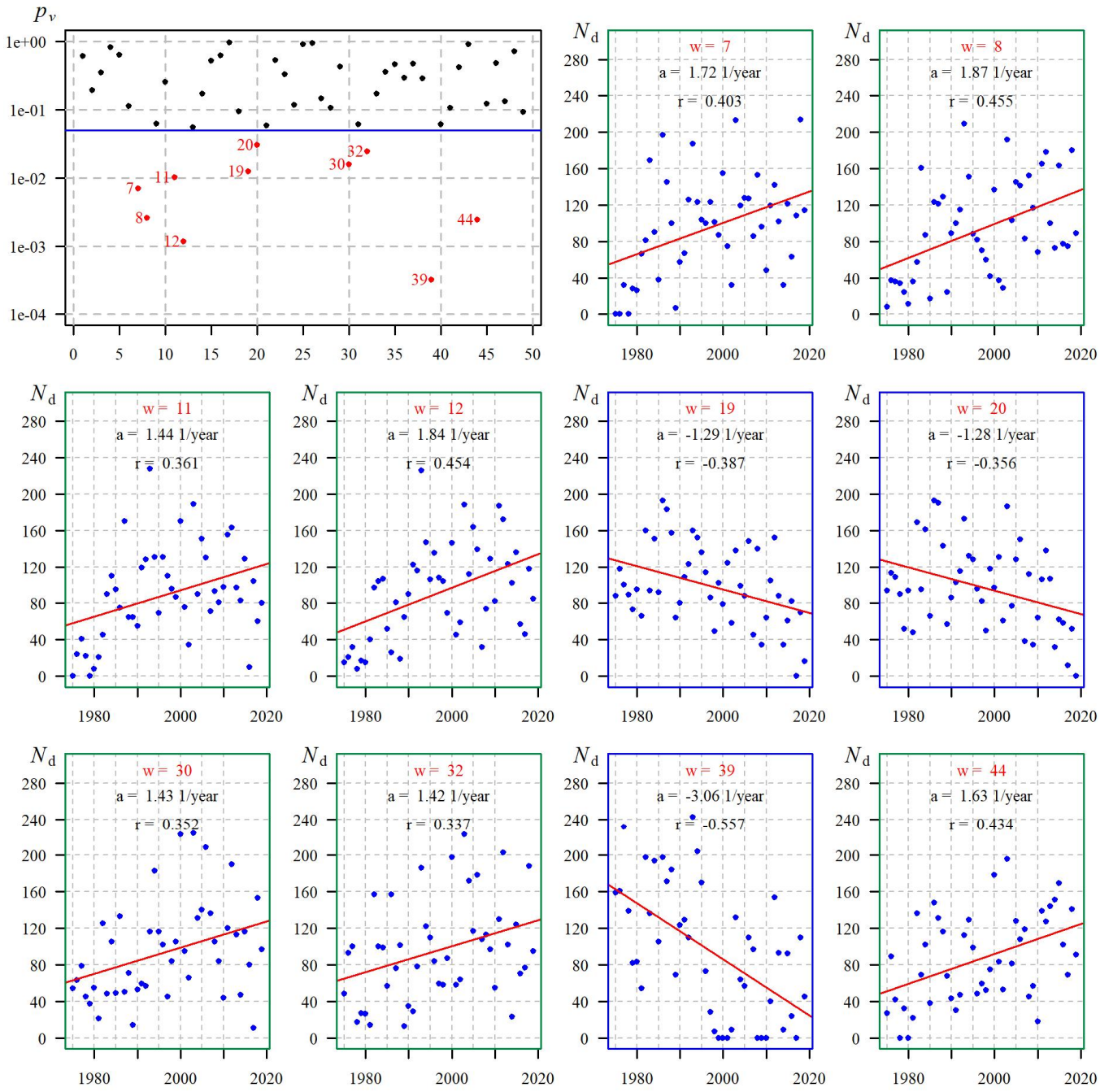


Fig. 9. The *p*-value obtained from the Mann-Kendall test for the time series of the number of drought days N_d at 49 cross-sections. Significant trends at 5% level are marked in red. The remaining graphs show the non-stationary (when $p_v < 0.05$) series N_d.

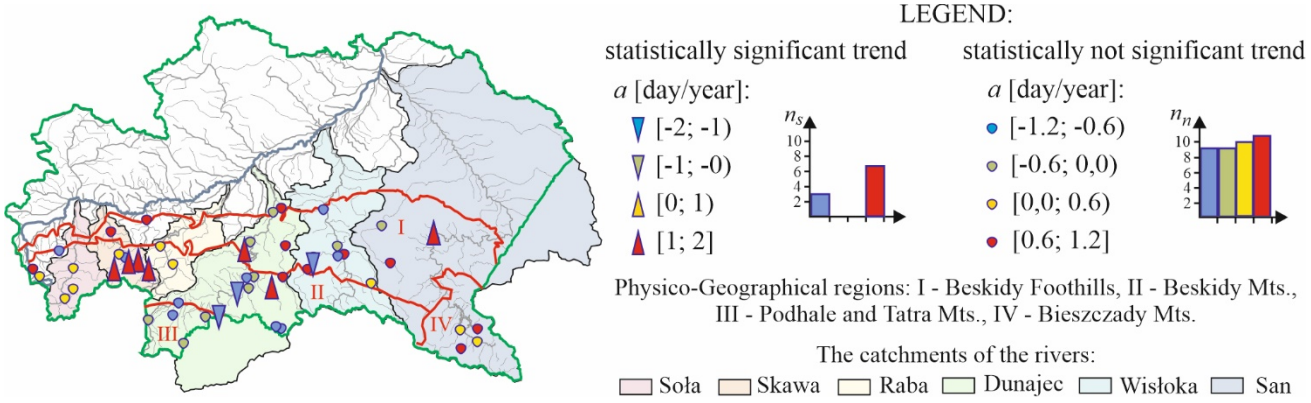


Fig. 10. The spatial distribution of the statistically significant/non-significant trends of the series of drought days N_d including the value of the slope coefficient *a*, grouped into four categories, within the physico-geographical regions.

cross-sections Krościenko (19) and Gołkowice (20) are located on the Dunajec River, below the reservoirs Czorsztyn-Niedzica (opened in 1997) and Sromowce Wyżne (opened in 1994).

In the majority of the studied area, the series of drought days N_d are stationary and the statistically non-significant directions of changes of series N_d are both increasing and decreasing (Fig. 10). In the region of Podhale and the Tatra Mts., the statistically non-significant trends of change to these series are downward, while in the Bieszczady Mts. - upward. In the Beskidy Mts., these trends have different directions, however in the eastern part of this area, in the catchments of the rivers: Soła, Skawa and Raba, the direction of changes of the N_d is predominantly increasing.

CONCLUSIONS

This work contains a comprehensive assessment of hydrological droughts in the Polish Carpathians in the multi-year hydrological period 1975–2019. Mean drought duration and drought volumes in a studied area indeed increase with the altitude of the location of a gauging station elevations.

According to the World Meteorological Organization, 2015 was the warmest year since 1961 (WMO, 2016) all over the world. The following years, however, were just as warm, and some even warmer (WMO, 2021). Therefore, significant droughts have been observed in Poland in recent years. Droughts have been observed even in the Polish Carpathians, i.e. in the highest-located area in Poland, though the largest hydrological drought events in the analyzed multi-year period occurred in 2003 and 1986.

Droughts in the Beskidy and Bieszczady Mountains typically occur in the summer and autumn. Droughts usualy begin in July or August, when is most often warm, there is little precipitation and the lowest monthly river outflows per year are observed.

Due to spring thaws, the highest monthly outflows in Poland occur in March and April. Owing to the fact that the droughts in these regions under consideration rarely begin in March or April, the number of drought days is the lowest in April.

The Podhale and Tatra Mountains are the highest part of the Carpathians, where it is colder, there is higher total annual precipitation and spring thaws occur later than in the other part of the Carpathians. For these reasons, the droughts begin here - in the autumn and winter, they begin in the period between September and February (most commonly in January) and the lowest number of drought days in this region is observed in May and June.

In the Polish Carpathians, the greatest hazard of long lasting and of high volume droughts occur in the Podhale and Tatra Mountains, whereas the lowest - in the Bieszczady Mountains or the catchments of the rivers: Soła, Skawa and Raba. Drought events in the eastern part of the studied area, the Beskidy Mountains catchments of the rivers: Small Vistula, Dunajec, Wisłok and San, are most commonly of average length and volume. Despite of high annual total precipitation and river flows, long droughts are observed in the Tatra Mountains in winter. This may be the result of decreasing monthly amounts of precipitation during the year (starting from September), as well as the fact that winter precipitation is often not in liquid form, but in a form snow. Usually, winter in Poland is the time of renewing water resources; retained precipitation in the snow cover is, among others, an important source of, among others plant supplies in early spring. In recent years, we have observed warmer winters, with less snow cover. This reduces winter retention and leads to an increase in hydrological droughts in summer (also in the lower lying areas).

A statistically significant trend was identified in ten out of 49 drought days series: seven were positive and three were negative. The positive trends may come as a result of the global warming, while the negative trends were identified at the stations located on a river below the reservoirs built between 1975 and 2019, which would suggest that these stations are affected by water management on these reservoirs.

REFERENCES

Antofie, T., Naumann G., Spinoni, J., Vogt, J., 2015. Estimating the water needed to end the drought or reduce the drought severity in the Carpathian region. Hydrol. Earth Syst. Sci., 19, 177–193.

Baran-Gurgul, K., 2018. A comparison of three parameter estimation methods of the gamma distribution of annual maximum low flow duration and deficit in the Upper Vistula catchment (Poland). ITM Web of Conferences. 23.

Boczoń, A., Kowalska, A., Dudzińska, M., Wróbel, M., 2016. Drought in Polish Forests in 2015. Pol. J. Environ. Stud., 25, 5, 1857–1862.

Czarnecka, H. (Eds.), 2005. Atlas of the hydrographic division of Poland. Institute of Meteorology and Water Management, Warsaw. (In Polish.)

Demuth, S., Stahl, K., 2001. Assessment of the Regional. Impact of Droughts in Europe (ARIDE) – Final Report. University of Freiburg, Institute of Hydrology, Freiburg.

Espinosa, L.A., Portela, M.M., Rodrigues, R., 2019. Spatio-temporal variability of droughts over past 80 years in Madeira Island. J. Hydrol. Reg. Stud., 25, 100623.

Fendeková, M., Gauster, T., Labudová, L., Vrablíková, D., Danáčová, Z., Fendek, M., Pekárová, P., 2018. Analysing 21st century meteorological and hydrological drought events in Slovakia. J. Hydrol. Hydromech., 66, 4, 393–403.

Fleig, A., 2004. Hydrological Drought – A comparative study using daily discharge series from around the world. MSc thesis (Diplomarbeit). Institut für Hydrologie, Albert-Ludwigs-Universität Freiburg, Germany.

Fleig, A.K., Tallaksen, L.M., Hisdal, H., Demuth, S., 2006. A global evaluation of streamflow drought characteristics. Hydrol. Earth Syst. Sci., 10, 535–552.

Gustard, A., Demuth, S. (Eds.), 2008. Manual of Low-flow. Estimation and Prediction. Operational Hydrology Raport No. 50. World Meteorological Organization. WMO. No. 1029.

Hamed, K.H.; Rao, A.R., 1998. A modified Mann–Kendall trend test for autocorrelated data, J. Hydrol., 204, 182–196.

Helsel, D.R., Hirsch, R.M., Ryberg, K.R., Archfield, S.A., Gilroy, E.J., 2020. Statistical Methods in Water Resources. Techniques and Methods, book 4, chap. A3. U.S. Geological Survey, 458 p. https://doi.org/10.3133/tm4a3

Hisdal, H., Tallaksen, L.M., 2000. Drought Event Definition. Technical Report No. 6, Assessment of the Regional Impact of Droughts in Europe. University of Oslo, Oslo.

Hisdal, H., Stahl, K., Tallaksen, L.M., Demuth, S., 2001. Have streamflow droughts in Europe become more severe or frequent? Int. J. Climatol., 21, 317–333.

IMWM-NRI, 2021. The Climate in Poland 2020. Report.

Jakubowski, W., 2011. Probability distributions in hydrological drought estimation. Wrocław University of Environmental and Life Sciences, Wrocław. (In Polish.)

Jakubowski, W., 2015. On the instabilities of estimated distributions of the POT (Peak Over Threshold) low flow characteristics. Meteorol., Hydrol. Water Manage., 3, 2, 33–38.

Jokiel, P., Marszelewski, W., Pociask-Karteczka, J., 2017.

Hydrology of Poland, (Polish Scientific Publishers PWN SA, Warszawa. (In Polish.)
Kendall, M.G., 1975. Rank Correlation Methods. 4th Ed. Charles Griffin, London.
Klimaszewski, M., 1972. Karpaty Wewnętrzne. In: M., Klimaszewski (Ed.): Polish Geomorphology. PWN, Warsaw. (In Polish.)
Kostrzewski, A., Krzemień, K., Migoń, P., Starkel, L., Winowski, M., Zwoliński, Z. (Eds.), 2021. Contemporary transformations of the relief of Poland. The Association of Polish Geomorphologists. Bogucki Scientific Publishing. Poznań. (In Polish.)
Krasowski, W., Tokarczyk, T., 2017. 2015-2016 hydrological drought in Poland compared to a multi-annual period. Gospodarka Wodna, 9/2017.
Laaha, G., Gauster, T., Tallaksen, L.M., Vidal, J.P., Stahl, K., Prudhomme, C., Heudorfer, B., Vlnas, R., Ionita, M., Van Lanen, H.A.J., Adler, M.J., Caillouet, L., Delus, C., Fendekova, M., Gailliez, S., Hannaford, J., Kingston, D., Van Loon, A.F., Mediero, L., Osuch, M., Romanowicz, R., Sauquet, E., Stagge, J.H., Wong, W.K., 2017. The European 2015 drought from a hydrological perspective. Hydrol. Earth Syst. Sci., 21, 3001–3024.
Lorenc, H., Markiewicz, M., Sasim, M., 2008. Droughts in Poland, with particular emphasis on 2006 - history, causes, intensity, range, effects, conclusions. News of MHWM, 1–2. (In Polish.)
Mann, H.B., 1945. Nonparametric tests against trend. Econometrica, 13, 3, 245–259.
Ministry of the Environment, 2013. Polish National Strategy for Adaptation to Climate Change (NAS 2020) with the perspective by 2030.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol., 391, 1–2, 202–216.
Niedźwiedź, T., Obrębska-Starklowa, B., 1991. Climate. In: Dynowska, I., Maciejewski, M. (Eds.): Upper Vistula River Basin - monograph. Vol. I. PWN, Warsaw. (In Polish.)
Ozga-Zielińska, M., Brzeziński, J., 1997. Applied Hydrology. PWN, Warsaw. (In Polish.)
Parry, S., Hannaford, J., Lloyd-Hughes, B., Prudhomme, C., 2012. Multi-year droughts in Europe: analysis of development and causes. Centre for Ecology and Hydrology, Hydrol. Res., 43.5, 689–706.
R Core Team, 2021. R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing, Austria, http://www.R-project.org/).
Sen, P.K., 1968. Estimates of Regression Coefficient Based on Kendall's tau. J. Am. Stat. Ass., 63, 324, 1379–1389.
Smakhtin, V.U., 2001. Low flow hydrology: a review. J. Hydrol., 240, 147–186.
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., 2018. Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geogr. Pol., 91, 2, 143–170.
Spinoni, J., Antofie, T., Barbosa, P., Bihari, Z., Lakatos, M., Szalai, S., Szentimrey, T., Vogt, J., 2013. An overview of drought events in the Carpathian Region in 1961-2010. Adv. Sci. Res., 10, 21–32.
Spinoni, J., Barbosa, P., De Jager, A., McCormick, N., Naumanna, G., Vogt, J.V., Magni, D., Masante, D., Mazzeschi, M., 2019. A new global database of meteorological drought events from 1951 to 2016. J. Hydrol.: Regional Studies, 22, 100593.
Stahl, K., 2001. Hydrological Drought. A Study across Europe. PhD Thesis. Freiburger Schriften zur Hydrologie no 15. Albert-Ludwigs Universität Freiburg, Freiburg, Germany.
Staśko, S., Buczyński, S., 2018. Drought and its effects on spring discharge regimes in Poland and Germany during the 2015 drought. Hydrological Sciences Journal, 63, 5, 741–751.
Sutanto, S.J., van Lanen, H.A.J., 2021. Streamflow drought: implication of drought definitions and its application for drought forecasting. Hydrol. Earth Syst. Sci., 25, 3991–4023.
Tallaksen, L.M., Hisdal, H., 1997. Regional analysis of extreme streamflow drought duration and deficit volume. FRIEND '91 - Regional Hydrology: Concepts and Models for Sustainable Water Resource Management IAI. In: Proceedings of the Postojna, Slovenia, Conference. AHS Publ. No. 246, pp. 141–150.
Tallaksen, L.M., Madsen, H., Clausen, B., 1997. On the definition and modelling of streamflow drought duration and deficit volume. Hydrol. Sci. J., 42, 1, 15–33.
Tallaksen, L.M., 2000. Streamflow drought frequency analysis. Drought and Drought Mitigation in Europe. Springer, pp. 103–117.
Tallaksen, L.M., van Lanen, H. (Eds.), 2004. Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater, vol. 48. Elsevier, 580 p.
Tallaksen, L.M., van Lanen, H.A.J., 2007. Key aspects of low flow and drought. Würzburg workshop on "Low flow and Droughts". In: Book of Abstracts, International CHR-Workshop – Expert Consultation, Würzburg, Germany, 25-26 September 2007, pp. 13–18.
Theil, H., 1950. A rank invariant method for linear and polynomial regression analysis. Nederl. Akad. Wetensch. Proc. Ser. A, 53, 386–392 (Part I), 521–525 (Part II), 1397–1412 (Part III).
Tlałka, A., 1982. Spatial differentiation of low flows in the basin of the upper Vistula. Rozprawy Habilitacyjne. Wydawnictwo Uniwersytetu Jagiellońskiego, Cracow, 63 p. (In Polish.)
Tokarczyk, T., 2010. Low flow as an indicator of hydrological drought. Institute of Meteorology and Water Management, Warsaw. (In Polish.)
Tokarczyk, T., 2013. Classification of low flow and hydrological drought for a river basin. Acta Geophysica, 61, 2, 404–421.
Tomaszewski, E., 2007. Maximum duration of extreme summer low flows in Central Poland and its determinants. Acta Universitatis Lodziensis, Folia Geogr. Physica, 8, 89–98. (In Polish.)
Tomaszewski, E., 2012. Multiannual and seasonal dynamics of low-flows in rivers of central Poland. Łódź University Press. (In Polish.)
Vido, J., Tadesse, T., Šustek, Z., Kandrík, R., Hanzelová, M., Škvarenina, J., Škvareninová, J., Hayes, M., 2015. Drought occurrence in Central European mountainous region (Tatra National Park, Slovakia) within the period 1961–2010. Adv. Meteorol., 2015, 248728.
Węglarczyk, S., 2014. Exceedance probability of selected low characteristic flows in mountain catchments. In: Infrastructure and Ecology of Rural Areas. Polish Academy of Science, IV/3/2014, pp. 1421–1429.
Wilhite, D.A., 2005. Drought and Water Crises Science. Tech-

nology and Management Issues. CLC Press, Taylor Francis Group, New York.
Wilhite, D.A., Glantz, M.H., 1987. Understanding the drought phenomenon: the role of definitions. In: Wilhite, D.A. Easterling, W.E., Wood, D.A. (Eds.): Planning for Drought: Toward a Reduction of Societal Vulnerability. Western Press, Boulder. CO, pp. 11–30.
WMO, 2016. https://public.wmo.int/en/media/press-release/2015-hottest-year-record (accessed on 19.01.2022).
WMO, 2021. 2020 was one of three warmest years on record. https://public.wmo.int/en/media/press-release/2020-was-one-of-three-warmest-years-record (accessed on 19.01.2022).
Wójcik, I., Doroszewski, A., Wróblewska, E., Koza, P., 2018. Agricultural drought in the cultivation of winter cereals in Poland in 2006–2017. Water-Environment-Rural Areas, 18, 4, 75–92. (In Polish.)
Yevjevich, V., 1967. An objective approach to definitions and investigations of continental hydrologic droughts. Hydrology Paper, 23, Colorado State University, Fort Collins, Colorado.
Zelenhasić, E., Salvai, A., 1987. A method of streamflow drought analysis. Water Resour. Manag., 23, 1, 156–168.
Zielińska, M., 1963. Statistical methods of working out low flows. Geophysical Review, VIII (XVI), 1–2, 75–87. (In Polish.)
Ziemońska, Z., 1973. Hydrographic conditions in the Polish West Carpathians. Geographical Studies, 103. Polish Academy of Science, Institute of Geography, Warsaw. (In Polish.)

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