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EARLIER EMERGENCE OF WINTER-SPRING MAXIMUM STREAMFLOW ACROSS POLAND, 1981–2020

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Abstract. Rivers in Poland present nival, nivo-pluvial and pluvio-nival water regimes with considerable peak flows occurring at the winter-spring turn in March, April or May. As climate warming occurs, the snow fraction of precipitation may change, and the atmospheric thaws might occur earlier, causing changes in the streamflow patterns. In this study, the date of the maximum streamflow occurrence at the winter-spring turn was analyzed during the period from 1981–2020 to detect possible changes in the river regime. Daily streamflow data from 102 river gauging stations across Poland were filtered with the moving average shifting horizon (MASH) method to filter out the short-term variability observed at daily and inter-annual scales. Then, the modified Mann-Kendall statistical test and the Theil-Sen slope were employed to assess the trend presence and magnitude of the observed date of the peak flow occurrence. A clear shift in the timing of the springtime maximum streamflow towards earlier in the year was revealed in many rivers across the country. An acceleration of the streamflow maximum was observed in 87 out of 102 analyzed rivers, ranging from –8 to –108 days. A 9-day delay was detected at one mountainous site. The other 14 rivers did not show a statistically significant shift.

Key words: winter-spring turn, peak flows, timing, trend, river regime change

Introduction

Streamflow is driven by a variety of hydrometeorological processes, the most important of which are precipitation and temperature. In snow-fed regions, variations in the snow amount, duration and timing can have a significant impact on water resources that are important for freshwater ecosystems and human activities (Sturm *et al*. 2017; Peters-Lidard *et al*. 2021). Currently, there is growing evidence from both regional and local studies that warming air temperatures impact snowfall patterns and change the snowmelt-influenced streamflow (Bell *et al*. 2016; Dudley *et al*. 2017; Ford *et al*. 2021; Rasouli *et al*. 2022; Somorowska 2023). Moreover, winter warming and snow droughts may propagate into the summer streamflow droughts, which are projected to occur even more frequently in the future (Demaria *et al*. 2016; Dierauer *et al*. 2021; Patterson *et al*. 2022). Thus, it is essential to understand how the timing of the winter-spring streamflow has changed over historical periods (Steward *et al*. 2004; Hodgkins, Dudley 2006; Wagner *et al*. 2021) and how the timing of peak flows is projected to shift in the future (Byun *et al*. 2019).

In Poland, climate change signals have been observed in several meteorological characteristics (Szwed *et al*. 2017; Falarz, Bednorz 2021; Tom-

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czyk *et al*. 2021). From 1951–2018, the air temperature trend rates in winter exceeded 0.3°C/decade (Ustrnul *et al*. 2021), and the number of days with snow cover significantly decreased (Falarz, Bednorz 2021). Moreover, the snow water equivalent also decreased over the period 1967–2020, with the snow cover stability not yet significantly disturbed (Wibig, Jędruszkiewicz 2023). The shortening of thermal winters (Czernecki, Miętus 2017) affected the streamflow magnitude and timing (Venegas-Cordero *et al.* 2022, 2023). Temporal changes in selected streamflow characteristics have been examined based on the seasonality and circular statistics (Jokiel, Stanisławczyk 2016; Piniewski *et al.* 2018; Wrzesiński, Sobkowiak 2018; 2020). Venegas-Cordero *et al.* (2022) analyzed selected river flood indicators (magnitude, frequency and timing) for 146 gauging stations using the annual and sub-annual maximum daily flow and peak-over threshold approaches. A mixed pattern of winter-half flood occurrences was found in the period 1981–2019; only for 5% of all streamflow gauges was the change in the maximum streamflow timing statistically significant at the 0.1 level. The following question arises: would another statistical method allow the identification of a long-term trend in a larger number of river gauging stations?

In this study, the date of the streamflow maximum occurrence in the winter-half of the water year was analyzed to detect possible changes in the hydrological regime. Unlike the method used in the work of Venegas-Cordero *et al.* (2022), a data filtering technique was applied before the temporal trends were examined. The specific objective of this paper was to investigate the presence, magnitude, direction and significance of changes in the timing of the maximum streamflow at the winter-spring turn using observed flow records. It was hypothesized that there was a shift to an earlier peak flow emergence. The analysis was conducted for selected river gauging stations in Poland for the last four decades (1981–2020). The results may support various environmental and climate change studies by providing information on the temporal shift in the winter-spring streamflow metric.

Study area

The winter-spring streamflow maximum was analyzed based on hydrometric data acquired from river gauging stations throughout the territory of Poland (Fig. 1). Across the country, river regimes result from complex climatic and physiographic conditions that may be impacted by human activity. According to the classification developed in the 1970s (Dynowska 1971), five major river regimes can be distinguished based on the highest of the March and April mean flows ($Q_{3,4}$), and the highest of the June, July and August mean flows ($Q_{6,7,8}$). A spatial delineation of river regimes in Poland can be found in Wrzesiński (2017), although the resource is not openly available in a digitized form. A strong nival regime is characterized by $Q_{3,4} > (1.8 \cdot Qmean)$, while a moderate nival regime is reported when $Q_{3,4} \in [1.3 \cdot Qmean, 1.8 \cdot Qmean]$; a weak nival regime is characterized by $Q_{3,4} < (1.3 \cdot Qmean)$. Two other river regime classes, namely nivo-pluvial and pluvio-nival regimes, are characterized by high flows in the spring months followed by high flows in the summer months. In the nivo-pluvial regime, the highest peak is due to snowmelt, while in the pluvio-nival regime, the highest peak corresponds to recharge by precipitation. March and April flows at the winter-spring turn result from the snowmelt recharging the rivers. In mountainous river basins, the winter-spring maximum may even occur in May (Wrzesiński 2017). All five river regime classes are influenced by seasonally occurring snowfall, the melting of which depends strongly on variable weather conditions. It is worth mentioning that snowmelt might occur not only in the spring months but also during atmospheric thaws that occur from December–February (Czarnecka, Nidzgorska-Lencewicz 2013). Generally, warming winters stimulate the reduction of the snow fraction of precipitation, causing the increased activity of hydrological processes.

Data

In this study, streamflow records from 102 river gauging stations over the territory of Poland were analyzed in the multi-year period of 1981–2021 (Fig. 1; Tab. 1A, B, C). The selected gauging stations belong to the river hydrometric network of Poland maintained by the Institute of Meteorology and Water Management – National Research Institute in Warsaw, Poland (IMGW 2023). The data set contains rivers representing the full spectrum of water regimes that occur in Poland; they are located in the coastal region and across lowlands, highlands and mountains. Daily streamflow data covering 40 water years were acquired from IMGW-PIB (2023). In Poland, a water year

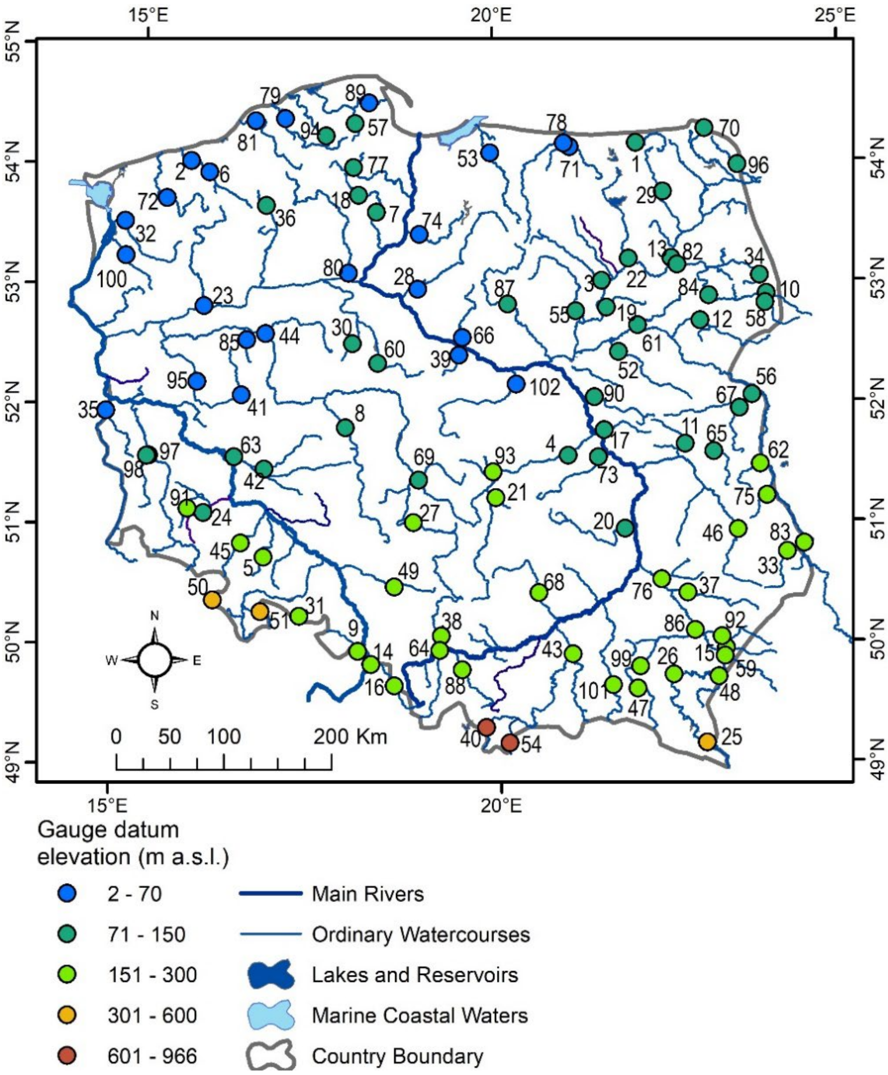

Fig. 1. Location of the river gauging stations over the territory of Poland. The location numbering is consistent with the numbering given in Tables 1A, B, C. The colored dots depict gauge datum elevation

is defined as the period from November 1 to October 31 and is designated by the year in which it ends. Thus, the so-called winter-half of the water year lasts from November to April. In case of the Dunajec and Białka rivers, an extended period was analyzed (including May), taking into account the timing of the spring peak flows.

The Koniówka gauge station at Dunajec (Fig. 1; Tab. 1B, No.=40) is located at 726 m a.s.l. and the Łysa Polana gauge at Białka (Fig. 1; Tab. 1B; No.=54) is at 966 m a.s.l. Both gauge stations are located in the mountainous region, where the spring onset starts at least 30 days later than in the Polish interior (Czernecki, Miętus 2017). For consistency, river basins with almost complete daily records during the 40-year period of 1981–2020 were selected. The drainage area ranges from 49 km^2 to 8984 km^2 (average of 1765 km^2).

Methods

In order to address the above research objectives, this study followed four main steps: (1) streamflow data filtration using the moving average shifting horizon (MASH) method (Anghileri *et al.* 2014), (2) the selection of the date of emergence of the winter-spring streamflow maximum coded as a day of the water year (DofWY), (3) trend detection in the date of the winter-spring streamflow maximum (DofWY) using the modified Mann-Kendall test (Mann 1945; Kendall 1975; Hamed, Rao 1998) and (4) the assessment of the trend line slope using the Theil-Sen slope method (Theil 1950; Sen 1968) and the shift in the winter-spring maximum streamflow. First, streamflow data were smoothed over the same block of days in consecutive years represented in the MASH method

Table 1A

Z-statistic of the modified Mann-Kendall test, followed by the Theil-Sen slope estimate used to evaluate the shift in the timing of the winter-spring streamflow maximum emergence (list of river basins numbered 1–35)
Statistically significant trends at the 0.05 significance level are marked with an asterisk (*)

No.	Gauge	River	Drain-age area [km^2]	Gauge datum elevation [m a.s.l.]	Z-statistic	Theil-Sen slope [day/year]	40-year shift [day]
1	Banie Mazurskie	Gołdapa	548	100.4	-2.006*	-0.50	-20
2	Bardy	Parsęta	2869	3.8	-3.292*	-1.86	-74
3	Białobrzeg Bliższy	Omulew	1864	94.5	-6.954*	-0.92	-37
4	Białobrzegi	Pilica	8660	112.1	-3.501*	-0.73	-29
5	Białobrzezie	Ślęza	177	159.6	-2.083*	-0.60	-24
6	Białogard	Parsęta	1128	19.4	-2.217*	-1.60	-64
7	Błędno	Wda	1369	80.4	-2.736*	-0.77	-31
8	Bogusław	Prosna	4286	88.0	-1.632	–	–
9	Bojanów	Psina	521	195.8	-2.234*	-0.52	-21
10	Bondary	Narew	1086	135.1	-3.348*	-1.00	-40
11	Borki	Bystrzyca	682	134.7	-2.923*	-0.80	-32
12	Brańsk	Nurzec	1204	122.3	-4.153*	-1.00	-40
13	Burzyn	Biebrza	6931	98.9	-5.178*	-0.93	-37
14	Chałupki	Odra	4659	192.8	-3.071*	-0.64	-26
15	Charytany	Szkło	755	183.0	-2.278*	-0.50	-20
16	Cieszyn	Olza	449	266.2	-4.212*	-0.62	-25
17	Cyganówka	Wilga	533	104.1	-2.781*	-0.59	-24
18	Czarna Woda	Wda	845	111.1	-3.263*	-2.25	-90
19	Czarnowo	Orz	520	89.8	-3.977*	-0.93	-37
20	Czekarzewice	Kamienna	1887	135.5	-2.908*	-0.64	-26
21	Dąbrowa	Czarna	945	172.9	-2.091*	-0.65	-26
22	Dobrylas	Pisa	4087	98.2	-2.295*	-0.50	-20
23	Drawiny	Drawa	3279	30.0	-6.901*	-1.54	-62
24	Dunino	Kaczawa	758	135.7	-4.164*	-0.67	-27
25	Dwernik	San	418	512.1	-0.060	–	–
26	Dynów	San	2944	234.9	-0.017	–	–
27	Działoszyn	Warta	4093	172.7	-2.651*	-0.56	-23
28	Elgiszewo	Drwęca	4973	45.8	-2.984*	-0.80	-32
29	Ełk	Ełk	831	119.8	-2.262*	-1.67	-67
30	Gębice	Mała Noteć	176	78.2	-5.865*	-1.00	-40
31	Głuchołazy	Biała Głuchołaska	285	281.1	-2.149*	-0.25	-10
32	Goleniów	Ina	2132	1.9	-3.471*	-1.46	-58
33	Gozdów	Huczwa	1196	180.8	-2.838*	-0.71	-29
34	Gródek	Supraśl	208	137.8	-9.921*	-0.73	-29
35	Gubin	Nysa Łużycka	4082	37.7	-2.038*	-0.85	-34

Table 1B

Z-statistic of the modified Mann-Kendall test, followed by the Theil-Sen slope estimate used to evaluate the shift in the timing of the winter-spring streamflow maximum emergence (list of river basins numbered 36–70)
Statistically significant trends at the 0.05 significance level are marked with an asterisk (*)

No.	Gauge	River	Drain-age area [km^2]	Gauge datum elevation [m a.s.l.]	Z-statistic	Theil-Sen slope [day/year]	40-year shift [day]
36	Gwda Wielka	Gwda	443	132.1	-2.260*	-0.38	-15
37	Harasiuki	Tanew	2030	164.7	-2.416*	-0.63	-25
38	Jeleń	Przemsza	2004	231.1	-2.448*	-0.93	-37
39	Klusek	Skrwa Lewa	356	69.8	-2.383*	-1.07	-43
40	Koniówka	Dunajec	132	725.9	-1.876	–	–
41	Konojad	Mogilnica	722	63.8	-3.686*	-0.80	-32
42	Korzeńsko	Orla	1217	85.2	-4.589*	-0.90	-36
43	Koszyce Wielkie	Biała	954	189.8	-2.516*	-0.93	-37
44	Kowanówko	Wełna	2605	51.4	-3.586*	-0.58	-23
45	Krasków	Bystrzyca	679	176.4	-4.198*	-0.69	-28
46	Krasnystaw	Wieprz	3013	174.0	-2.584*	-0.68	-27
47	Krosno	Wisłok	591	256.9	-4.819*	-0.53	-21
48	Krówniki	Wiar	786	191.5	-1.649	–	–
49	Krupski Młyn	Mała Panew	666	224.0	-2.668*	-0.60	-24
50	Kudowa Zdrój-Zakrze	Klikawa	49	374.7	-3.888*	-0.23	-9
51	Lądek Zdrój	Biała Lądecka	163	420.6	-2.906*	-0.43	-17
52	Łochów	Liwiec	2475	95.1	-3.348*	-0.96	-38
53	Łozy	Pasłęka	2009	20.6	-1.828	–	–
54	Łysa Polana	Białka	64	965.7	2.227*	0.23	9
55	Maków Mazowiecki	Orzyc	1936	90.2	-2.719*	-0.82	-33
56	Malowa Góra	Krzna	3054	127.8	-2.346*	-0.50	-20
57	Miłoszewo	Łeba	175	121.4	-5.065*	-2.46	-98
58	Narewka	Narewka	609	138.8	0.031	–	–
59	Nienowice	Wisznia	1188	178.8	-0.986	–	–
60	Noć Kalina	Noteć	416	76.3	-3.738*	-1.60	-64
61	Nowe Kaczkowo	Brok	732	96.5	-4.283*	-1.00	-40
62	Okuninka	Włodawka	589	154.4	-0.024	–	–
63	Osetno	Barycz	4575	77.6	-4.606*	-0.85	-34
64	Oświęcim	Soła	1358	225.9	-2.134*	-0.28	-11
65	Parczew	Piwonia	404	143.2	-2.803*	-0.67	-27
66	Parzeń	Skrwa	1507	67.5	-2.202*	-1.00	-40
67	Perkowice	Zielawa	877	134.4	-2.465*	-0.56	-23
68	Pińczów	Nida	3330	183.6	-2.496*	-0.50	-20
69	Podgórze	Widawka	2368	139.8	-2.108*	-0.44	-18
70	Poszeszupie	Szeszupa	188	119.0	-1.381	–	–

Table 1C

Z-statistic of the modified Mann-Kendall test, followed by the Theil-Sen slope estimate used to evaluate the shift in the timing of the winter-spring streamflow maximum emergence (list of river basins numbered 71–102)
Statistically significant trends at the 0.05 significance level are marked with an asterisk (*)

No.	Gauge	River	Drain-age area [km^2]	Gauge datum elevation [m a.s.l.]	Z-statistic	Theil-Sen slope [day/year]	40-year shift [day]
71	Prosna	Guber	1559	28.9	-2.107*	-0.77	-31
72	Resko	Rega	1132	31.9	-2.489*	-1.25	-50
73	Rogożek	Radomka	2064	107.8	-3.983*	-0.71	-29
74	Rogóźno 2	Osa	1138	31.4	-2.023*	-0.39	-16
75	Ruda-Opalin	Uherka	431	166.4	0.051	–	–
76	Ruda Jastkowska	Bukowa	649	153.2	-5.070*	-0.59	-24
77	Sarnowy	Wierzyca	134	143.4	-3.671*	-1.67	-67
78	Sępopol	Łyna	3632	26.3	-2.923*	-1.00	-40
79	Słupsk	Słupia	1453	12.8	-2.358*	-1.88	-75
80	Smukała	Brda	4450	39.8	-3.049*	-1.46	-58
81	Stary Kraków	Wieprza	1535	5.4	-3.061*	-2.33	-93
82	Strękowa Góra	Narew	7199	99.3	-3.486*	-0.92	-37
83	Strzyżów	Bug	8984	171.7	0.340	–	–
84	Suraż	Narew	3419	116.1	-2.668*	-0.82	-33
85	Szamotuły	Sama	398	61.2	-4.173*	-1.50	-60
86	Tryńcza	Wisłok	3515	165.2	-3.042*	-0.89	-36
87	Trzciniec	Wkra	1943	105.4	-3.339*	-0.64	-26
88	Wadowice	Skawa	833	254.2	-2.119*	-0.44	-18
89	Wejherowo	Reda	406	19.6	-3.807*	-1.82	-73
90	Wólka Mlądzka	Świder	861	96.7	-2.329*	-0.69	-28
91	Zagrodno	Skora	165	181.3	-2.040*	-0.20	-8
92	Zapałów	Lubaczówka	858	187.4	-4.286*	-0.64	-26
93	Zawada	Wolbórka	605	159.5	-0.660	–	–
94	Zawiaty	Łupawa	72	112.4	-2.159*	-2.71	-108
95	Zbąszyń	Obra	1297	50.5	-2.967*	-0.67	-27
96	Zelwa	Marycha	368	120.8	-1.445	–	–
97	Żagań	Bóbr	4258	92.0	-2.641*	-0.75	-30
98	Żagań	Czerna W.	899	98.2	-2.320*	-0.67	-27
99	Żarnowa	Wisłok	1433	213.6	-2.991*	-0.73	-29
100	Żelewo	Płonia	1033	12.0	-5.031*	-1.28	-51
101	Żółków	Wisłoka	583	225.0	-4.742*	-0.46	-18
102	Żuków	Bzura	7059	67.5	-2.074*	-0.52	-21

by the "w" parameter, and the "Y" parameter describes the number of years over which the daily values were averaged. Here, the parameter "w" was assumed to be equal to 10 days, and the parameter "Y" was assumed to be equal to 10 years. The applied averaging method filters out the short-term variability observed at daily and inter-annual scales. It reveals the multi-year changes in the streamflow seasonality. In the second step, the maximum value in the winter-half of each water year was selected and its occurrence date was identified. The first ten-year averaged series of daily flows covers the period 1981–1990, and the last one covers 2011–2020. Thus, for each river gauging station, 31-element time series with dates were prepared to be further tested for the trend. The date of the maximum streamflow emergence was coded as a numerical value counted from November 1. For example, the date of March 31 is represented by the value of 151 in the 365-day smoothed streamflow data. In the third step, trend analysis was conducted using the modified Mann-Kendall test at the 0.05 significance level (Fatichi 2024). Then, the Theil-Sen slope method was applied to calculate the magnitude of the trend (Harynuk 2024). The Theil-Sen slope is expressed in units of year/day. Negative values of the slope represent the shift towards an earlier emergence of the winter-spring streamflow maximum, while positive values represent a shift towards a postponed streamflow peak. Finally, the shift in the emergence of the winter-spring maximum streamflow was calculated by multiplying the number of years in the time series (40 years) by the Theil-Sen slope. The four-step calculation procedure was applied to all 102 gauging stations. The results of the analysis were visualized for six selected river basins representing the five types of water regimes occurring in Poland. Moreover, for these river basins, the monthly Pardé coefficient (PC: ratio of the monthly mean to the mean annual discharge in a multi-year period) (Pardé 1957) was calculated for the last 10-year period (2011–2020) and compared with that for the 30-year period (1981–2010).

Results

The change in the river runoff regime is revealed through the change in DofWY for the winter-spring peak flow, which is reported as "40-year shift" in Tab. 1A, B, C. The 40-year shift value varies considerably across the study area from –108 days (earlier occurrence) to 9 days (delayed occurrence) (Fig. 2). The highest number of cases (66 gauging stations) showed a 40-year shift ranging from –11 to –40 days. In 18 cases, the significant change was much higher, from –41 to over –100 days, and only three cases showed a shift from –8 to –10 days. A delayed peak flow was found in one case. Decreasing trends were confirmed in 87 out of 102 gauges (Fig. 3; Tab. 1A, B, C), while an increasing trend showed up in one mountainous gauge (Tab. 1B, No.=54). In 14 out of 102 gauging stations (15%), no trend was detected. These stations are located in the north-east in the Marycha (Tab. 1C, No.=96) and Szeszupa (Tab. 1B, No.=70) basins, in the east in the Narewka (Tab. 1B, No.=58), Włodawka (Tab. 1B, No =62), Uherka (Tab. 1C, No.=75) and Bug (Tab. 1C, No.=83) basins, in the south-east in the San (Tab. 1A, No.=25, 26), Wiar (Tab. 1B, No.=48) and Wisznia (Tab. 1B, No.=59) basins, in the south in the Dunajec Basin (Tab. 1B, No.=40) and in central Poland in the Prosna (Tab. 1A, No.=8) and Wolbórka (Tab. 1C, No.=93) basins. Overall, changes in the timing of the peak flow emergence at the winter-spring turn are widespread and strongly differentiated. Changing climate and physiographic conditions appear to be responsible for the river regime variations but human influence is not excluded.

Figure 4 provides a visual representation of the MASH results for the daily streamflow time series at the gauges representing three types of nival regimes. The assignment of rivers to specific river regime types can be found in Wrzesiński and Sobkowiak (2020). A weak nival regime is represented by the Słupia River (Fig. 4A; Tab. 1C, No.=79), a moderate nival regime is characteristic for the Wkra River (Fig. 4B; Tab. 1C, No.=87) and a strong nival regime is characteristic for the Liwiec River (Fig. 4C, Tab. 1B, No.=52). The color lines represent decadal averages of the daily streamflow, from the least recent (dark blue) to the most recent (dark red) decades. There is a distinct shift to earlier dates of the spring maximum streamflow in all three cases. The peak flows shift backward from the March-April turn to the February–March turn, accounting for an earlier emergence by –75, –26 and –38 days in the respective basins. Moreover, a significant shift to an earlier spring discharge can be observed, and the low flows in February are diminishing. The MASH results for rivers representing the nivo-pluvial regime (Wisłoka and San) and pluvio-nival regime (Dunajec) are provided

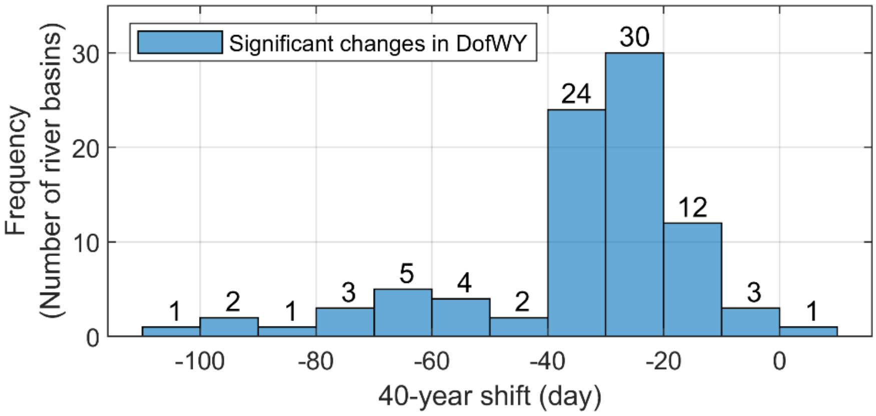

Fig. 2. Frequency histogram showing the number of river basins with significant changes in DofWY characterized by the 40-year shift

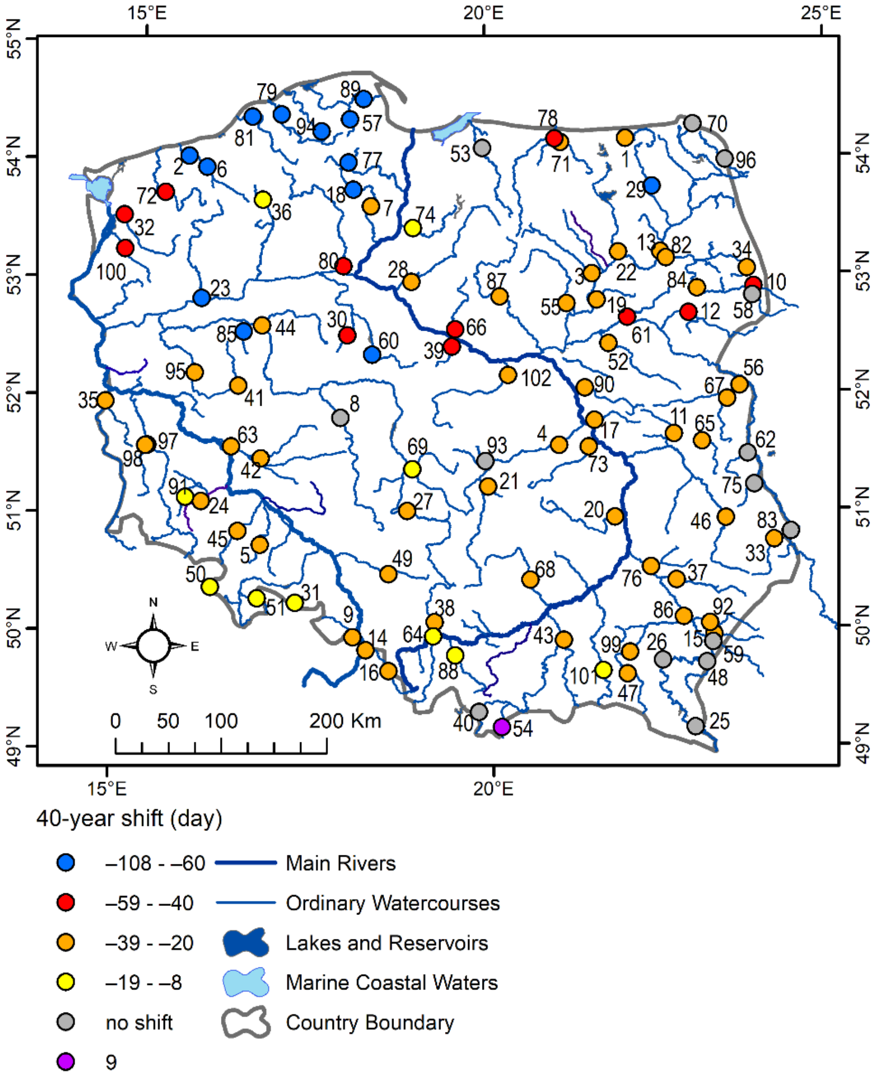

Fig. 3. 40-year shift in the emergence of the winter-spring maximum streamflow during the period 1981–2020
The location numbering is consistent with the numbering given in Tables 1A, B, C

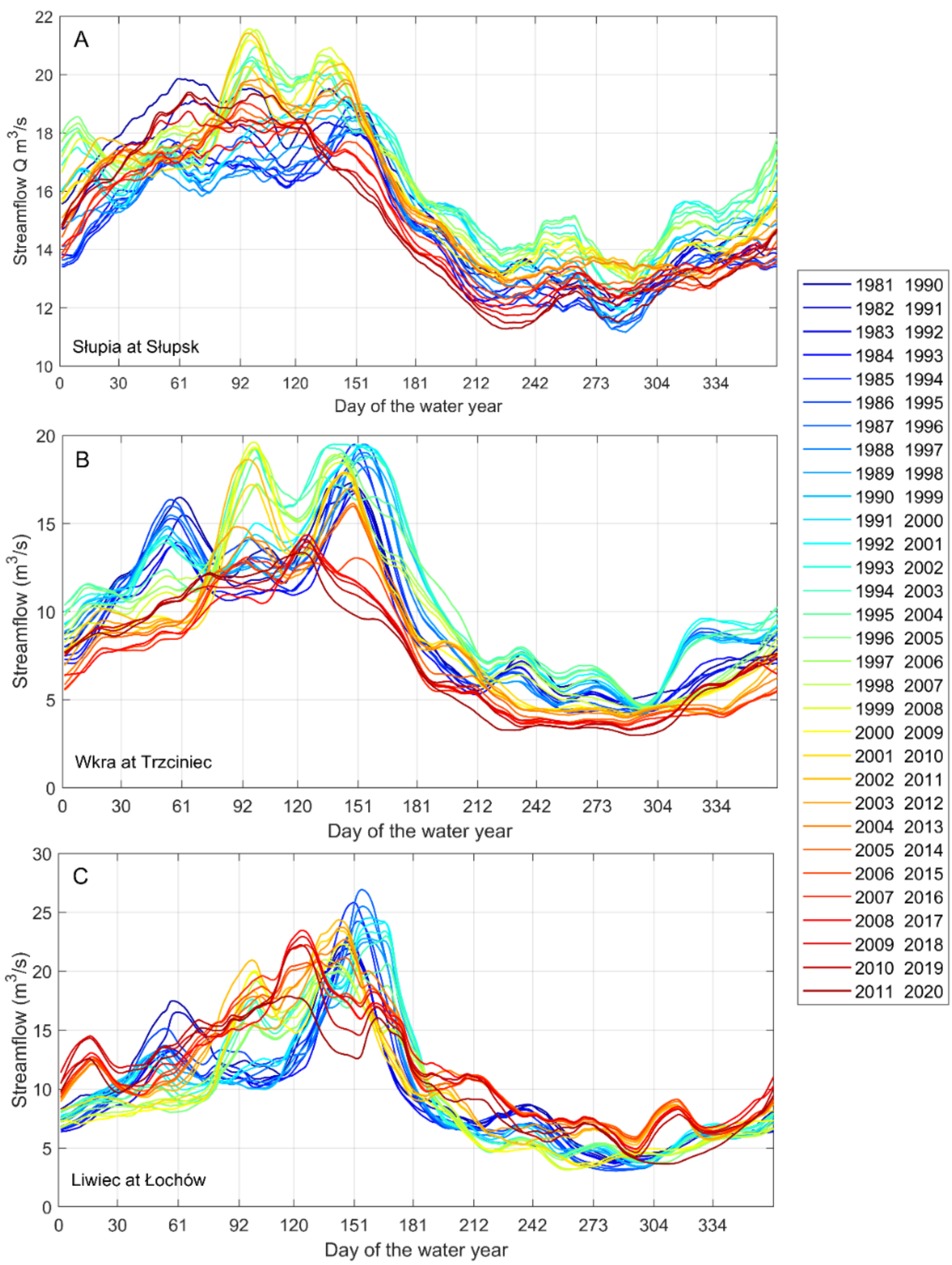

Fig. 4. Streamflow time series filtered with MASH in water years 1981–2020 for the following rivers:
A – Słupia at Słupsk (weak nival regime), B – Wkra at Trzciniec (moderate nival regime),
C – Liwiec at Łochów (strong nival regime)
The color lines represent the periods of averaging (31 periods of the 10-year moving averages)

in Figure 5. Here, the change in DofWY is statistically significant for the Wisłoka River (Fig. 5A; Tab. 1C, No.=101) but not for the San (Fig. 5B; Tab. 1A, No.=25) and Dunajec (Fig. 5C; Tab. 1B, No.=40) rivers. The 40-year shift was calculateed from the Theil-Sen trend lines visualized in Fig. 6–7. When considering multi-year river regime changes, the Pardé coefficient was employed to detect possible changes in the mean monthly streamflow distribution over the year for the selected six gauges. The Pardé coefficients of the most recent 10-year period (2011–2020) were compared with those for the 30-year averages for 1981–2010 (Fig. 8–9). A clear shift in the monthly values of the spring maximum was observed for the rivers with a nival regime;

it shifted from March to February in the Wkra and Liwiec basins (Fig. 8B, C) and from May to February in the Słupia Basin (Fig. 8A). A similar change was revealed in the Wisłoka and San rivers; the monthly spring maximum occurred one month earlier (Fig. 9A, B). However, the Dunajec River remained stable (Fig. 9C). It should be noted that 2011–2020 was the warmest decade on record, and the warmest six years on record globally were between 2015 and 2020 (WMO 2023). Moreover, an area of central Europe, centered on Germany, experienced a dry decade (WMO 2023), which was also reflected in Poland (Miętus, Marosz 2024).

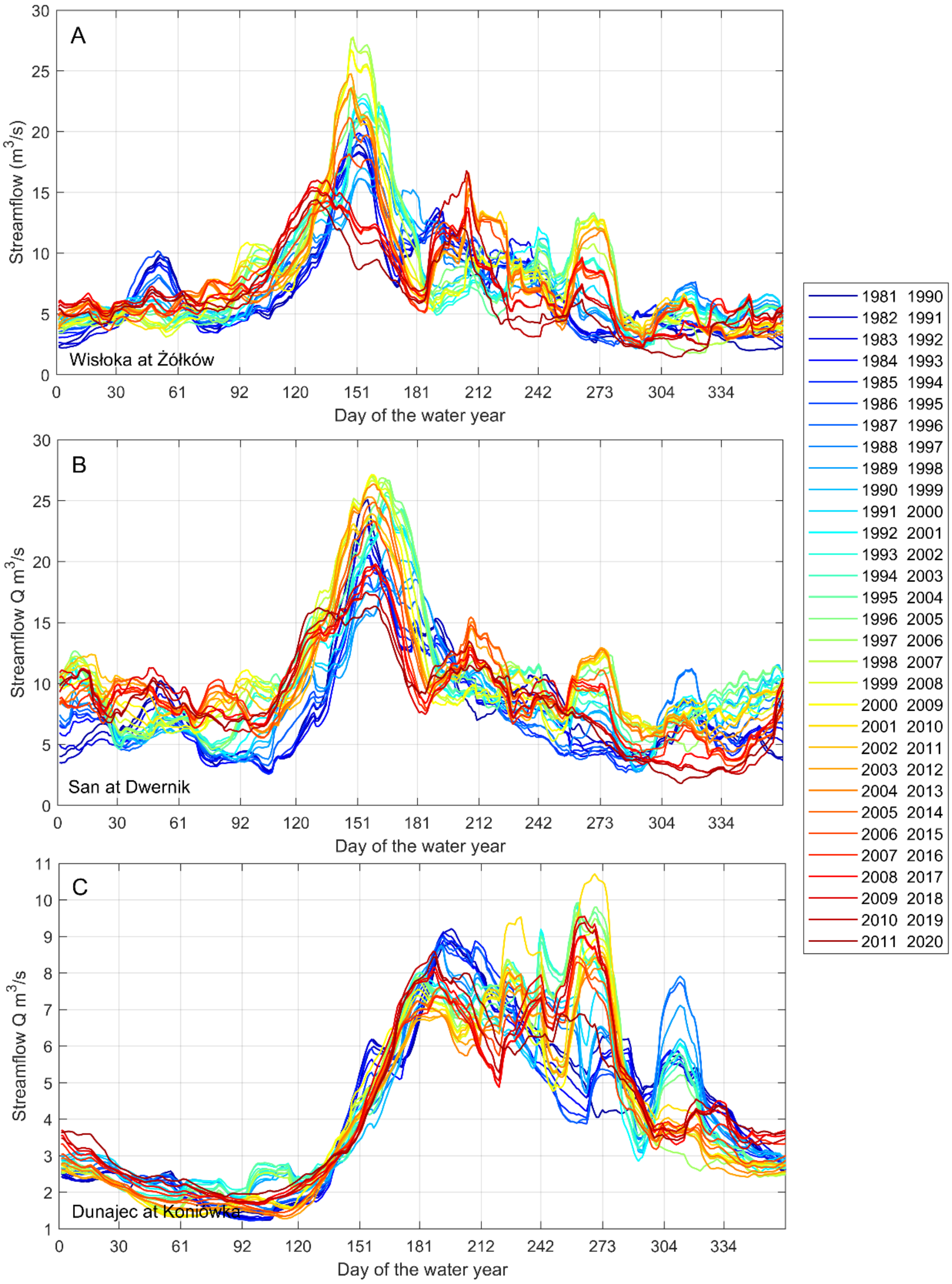

Fig. 5. Streamflow time series filtered with MASH in water years 1981–2020 for the following rivers: A – Wisłoka at Żółków (nivo-pluvial regime), B – San at Dwernik (nivo-pluvial regime) and C – Dunajec at Koniówka (pluvio-nival regime)
The color lines represent the periods of averaging (31 periods of the 10-year moving averages)

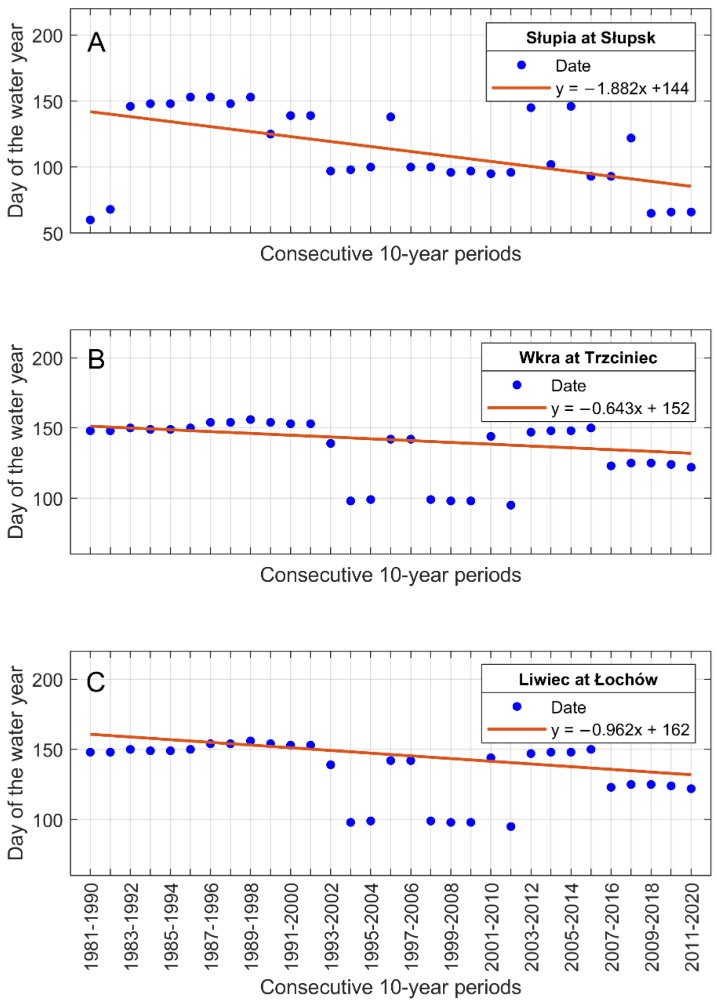

Fig. 6. Changes in the date of the winter-spring streamflow maximum (DofWY) from the 10-year moving averages for the following rivers:
A – Słupia at Słupsk, B – Wkra at Trzciniec, C – Liwiec at Łochów
The solid red lines show the Theil-Sen trend at the 0.05 significance level

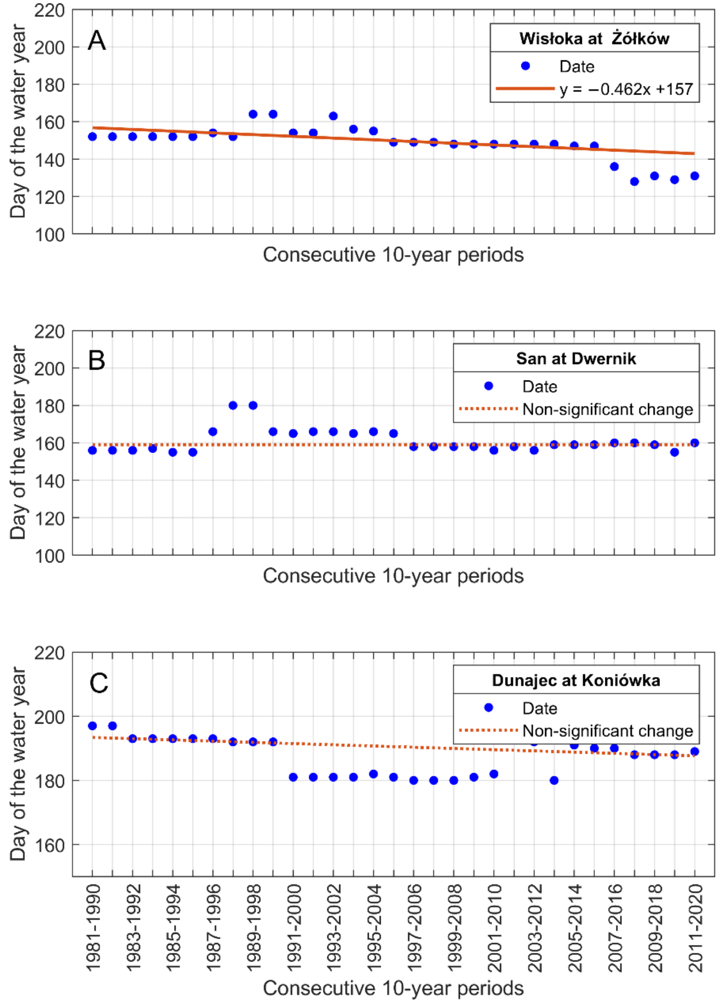

Fig. 7. Changes in the date of the winter-spring streamflow maximum (DofWY) from the 10-year moving averages for the following rivers:
A – Wisłoka at Żółków, B – San at Dwernik, C – Dunajec at Koniówka
The solid red line shows the Theil-Sen trend at the 0.05 significance level and the dotted red lines show non-significant changes

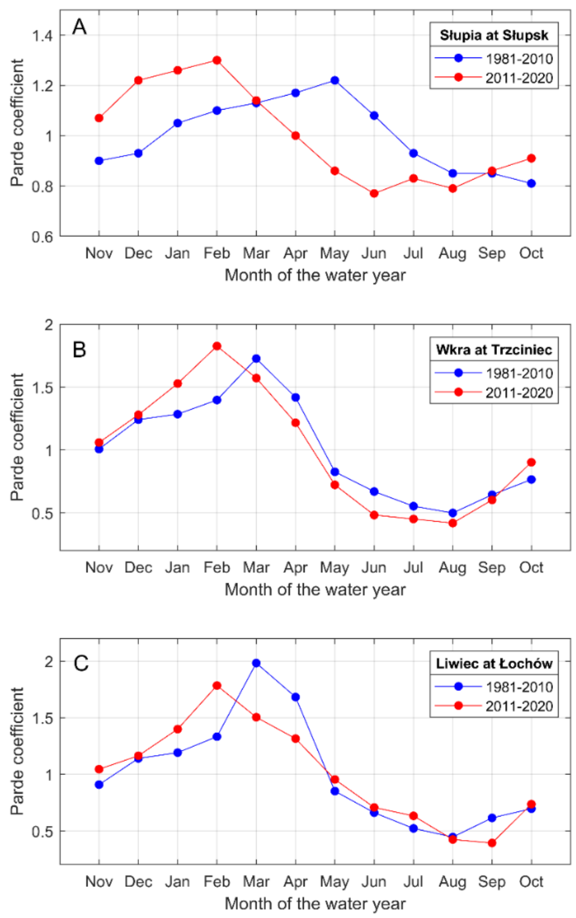

Fig. 8. The Pardé coefficient in two multi-year periods for the following rivers:
A –Słupia at Słupsk, B – Wkra at Trzciniec,
C – Liwiec at Łochów

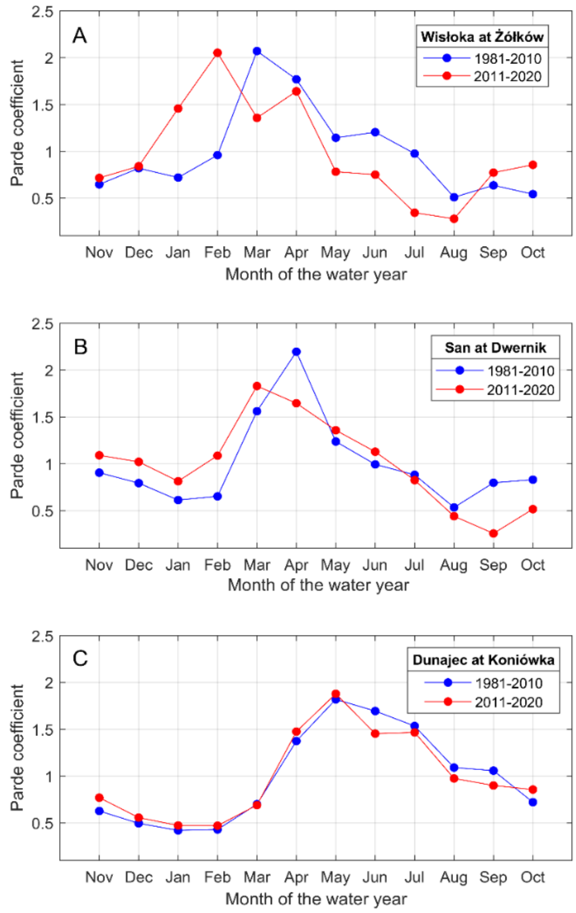

Fig. 9. The Pardé coefficient in two multi-year periods for the following rivers:
A – Wisłoka at Żółków, B – San at Dwernik,
C – Dunajec at Koniówka

Discussion

In this study, 40-year records (1981–2020) of the daily streamflow for 102 river basins across Poland were analyzed to explain possible changes in the dates of winter-spring maximum flows. An important result of this study is that there is a widespread shift of peak flows, which confirms the hypothesis regarding temporal runoff acceleration observed at many river gauging stations. However, a delayed peak flow occurrence was also confirmed, and it concerned one site at high elevation. Generally, advanced occurrences of the peak flow events are demonstrated in the majority of the analyzed stations. However, owing to the high differentiation in river regimes resulting from hydroclimatic complexity and physiographic features, the acceleration expressed by the number of days strongly varies across the country. At 87 analyzed gauge stations, the 40-year shift varies from –8 to –108 days, while at 14 gauges, changes were not detected. A possible reason for such changes is an increase in the air temperature during winter and spring causing atmospheric thaws, a higher rain fraction and mid-season snowmelt. All these factors might force an accelerated discharge during the cold period. The greatest advancement was observed over northwestern and western Poland, where the winter thaws occur most frequently (Czarnecka, Nidzgorska-Lencewicz 2013) and the thermal spring starts the earliest (Czernecki, Miętus 2017). The shift of the winter-spring maximum streamflow observed in daily records was reflected in the monthly values of the Pardé coefficient, especially in rivers representing the nival regime (Fig. 8). An earlier discharge maximum caused the streamflow reduction in consecutive months. For example, the Pardé coefficient increased in February, while it decreased in March, April and May. This finding is consistent with trends observed in Western Pomeranian river basins, which experienced a decrease in the spring and early summer specific discharge (Świątek, Walczakiewicz 2022). Shifts in the river regime were also detected in the 95th percentile time series of the spring streamflow analyzed from 1966–2006 in 16 basins across Poland (Piętka 2009). However, the center of mass of the flows did not change significantly in that period. Similarly, seasonality indices of river discharge in most of 40 analyzed rivers across Poland did not show trends in the period 1951–2010 (Jokiel, Stanisławczyk 2016). In contrast, more recent investigations conducted for the period 1981–2019 have shown a pattern of advanced river flood timing over southern Poland and delayed timing in northeastern and northwestern Poland (Venegas-Cordero *et al.* 2022). However, only 8 out of 146 stations showed trends at the 0.1 significance level, including two stations with accelerated peak flows in the south and six stations with delayed peak flows in the northeastern and northwestern parts. In this study, evidence of the advancement in the winter-spring maximum streamflow was found at many more stations across the whole country. Such a discrepancy between the results of this study and findings from previous investigations is caused by differences in the period of analysis and differences in the set of selected gauging stations and the applied methods. In this study, among 102 stations, 39 stations belong to the set selected by Venegas-Cordero *et al.* (2022), and the other 63 stations were analyzed for the first time. The advantage of this study is the inclusion of the latest multi-year period over which sequential analysis using the MASH approach was conducted. The application of the smoothing technique to filter out the short-term variability observed at daily and inter-annual scales helped to detect long-term trends. It is worth noting that signs of change in the date of the maximum river discharge at the winter-spring turn were investigated for other river basins across different hydroclimatic conditions. For example, an earlier timing of snowmelt runoff was observed for a period starting in the late 1940s in many rivers of western North America, and further changes were projected for the 21st century (Steward *et al.* 2007). Such an acceleration in the date of the spring daily maximum discharge was also shown for six large Russian river basins in the period 1960–2001 (Shiklomanov *et al.* 2007). In large German river basins, river regimes were considerably affected by environmental change (Bormann 2010).

Conclusions

This study adopted the MASH approach to examine the 40-year shift in the timing of the winter-spring streamflow in 102 river basins across Poland. A consistent pattern of acceleration in the cold-season maximum streamflow was observed at 85% of the analyzed gauge stations. The shift varied significantly within the range from –8 to –108 days. Warming spring temperatures and the shortening of thermal winters are probable reasons for such trends. On the other side, human impacts on river regimes are not excluded and might add to the transformation. In contrast, some basins located in the northeast, east and southeast did not show significant changes, which might be caused by the influence of a snowy humid climate with more persistent snow cover (Kottek *et al.* 2006). The gauge station located at high elevation showed a delayed signal, which might be caused by climate-driven changes in the snow regime. The spatial pattern is highly differentiated and differs from patterns found in previous research; thus, further studies are required using the enlarged set of gauging stations. Generally, this study contributes to the quantification of the multi-year trends in the date of the winter-spring peak flows, uncovering the regions that are most prone to river regime degradation.

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