CLIMATIC DETERMINANTS OF CHANGES IN THE ICE REGIME OF CARPATHIAN RIVERS

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Manuscript received: January 9, 2025
Revised version: March 1, 2025

Fukś M., Wiejaczka Ł., 2025. Climatic determinants of changes in the ice regime of Carpathian rivers. *Quaestiones Geographicae* 44(1), Bogucki Wydawnictwo Naukowe, Poznań, pp. 131–143. 4 figs, 4 tables.

Abstract: The study addresses the influence of climatic conditions on changes in the ice regime of Carpathian rivers (Central Europe) over the period 1980–2020. The main objective of this study is to identify interrelationships between air temperature, water temperature, river flow, and changes in the occurrence of ice cover (IC) in mountain areas. Rivers that are not significantly influenced by human activity (i.e. seminatural) were selected for analysis. Analyses were based on data obtained from 13 hydrological stations, 7 climatological stations, and the Climatic Research Unit gridded Time Series (CRU-TS) high-resolution climatological dataset. The study showed a decrease in the frequency of IC in the study area, reaching 7.25 days per decade, with the greatest changes recorded in November and February. At the beginning of the winter period (November), the decrease in the frequency of IC is mainly influenced by the increasing water temperature (by an average of 0.85°C per decade), whereas in the middle of the winter period (especially February), it is influenced by the increase in discharge of the studied rivers (by 1.1 m^3 per decade on average in February). Both the increase in water temperature and the increase in discharge during the winter period are due to the increase in air temperature, averaging 0.47°C per decade during the winter period.

Keywords: river ice cover, river ice regime, water temperature, discharge, climate change

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Introduction

Due to its periodic occurrence, river ice cover (IC) is among the most sensitive components of Earth's cryosphere to environmental change (Pawłowski 2017). The temporal and spatial variability of river IC formation is governed by a multitude of natural factors, including meteorological, hydrological, hydrodynamic, and geomorphological conditions, as well as the presence of riparian vegetation (Lind et al. 2016). Variability resulting from natural processes is superimposed onto influences arising from human activities, primarily from the emission of pollutants into rivers, the construction of hydraulic structures, and icebreaking actions aimed at reducing the risk of ice jams (e.g. Pawłowski 2017). Due to the high degree of complexity and the interplay of factors influencing river IC formation, the contemporary transformation of ice regimes in Earth's rivers remains incompletely understood (Fukś 2023).

Existing studies suggest that climate change has led to a marked decline in the frequency and extent of river IC over recent decades (e.g. Magnuson et al. 2000, Yang et al. 2020, Newton,

https://doi.org/10.14746/quageo-2025-0009
ISSN 2082-2103, eISSN 2081-6383

Mullan 2021, Fukś 2023). The primary factor influencing such changes in the occurrence of river IC is the global increase in air temperature (resulting from progressive climate change), which has been recorded especially since the second half of the twentieth century (Magnuson et al. 2000, Yang et al. 2020, Newton, Mullan 2021, Fukś 2023). It is estimated that, during the period 1980–2015, an increase in air temperature in the range of 0.4–0.5°C per decade in Central Europe (Gutiérrez et al. 2021) has led to elevated water temperatures in rivers (North et al. 2013, Marszelewski, Pius 2016, Graf, Wrzesiński 2020, Kędra 2020, Fukś 2024) and significant alterations in river flow regimes (Mostowik et al. 2019, Muelchi et al. 2021, Rajwa-Kuligiewicz, Bojarczuk 2024). These changes, in turn, have had profound influences on river ice regimes. Changes are recorded not only for large lowland rivers, for which long observational series are available, but also for mountain rivers, which are relatively less well studied in terms of ice processes (Thellman et al. 2021). Despite the intensive changes observed, there is a lack of detailed research on the mechanisms of IC disappearance on mountain rivers during winter periods. Consequently, it has become crucial to improve our knowledge of the factors determining the ice regime of flowing waters and to prioritise them. This is particularly important in mountain environments, which are characterised by highly dynamic hydrological processes (Viviroli, Weingartner 2004) and the significant impact of human activities on river ecosystems (Wohl 2013). In this context, the study of mountain areas is particularly important due to their key role in shaping water resources for present and future generations (Viviroli et al. 2007).

This study examines the role of hydrological factors, particularly flow variability and water temperature, in shaping the formation of IC on mountain rivers, which are typified by pronounced hydrological dynamics. Regarding the Polish portion of the Carpathians, this variability occurs due to variations in the hydrological regime throughout the year in the latitudinal system. To date, studies on changes in the ice regime of rivers in the Polish Carpathians have primarily focused on those resulting from human activities (Cybreska 1975, Soja, Wiejaczka 2014, Fukś 2024, Fukś et al. 2024). However, since air temperature is one of the main regulators of thermal processes in surface waters, this study addresses the influence of two key factors – water temperature and river flow – on the formation of IC in winter. Changes in both of these parameters are associated with ongoing climate change; therefore, it is crucial to determine their impact on the transformation of the river ice regime.

The main objective of this study is to identify the interrelationships between air temperature, river discharge, water temperature, and changes in the occurrence of IC in mountain areas. The analysis was carried out for selected seminatural rivers distributed within the Polish Carpathians (central Europe). To address the main objective of the study, the following specific objectives were distinguished:

- analysis of time trends in the number of days with IC at selected water gauge cross sections;
- analysis of time trends in air temperature in the study area within the Polish Carpathians;
- identification of temporal changes in the volume of flows of the studied rivers during the winter period;
- identification of changes in water temperature of the studied rivers during the winter period;
- identification of the impact of changes in the flow regime and water temperature on the characteristics of the ice regime of the studied rivers.

Study area, data, and methods

Study area

The rivers of the Polish Carpathian Mountains are a significant part of the Upper Vistula River basin, and the courses of the main rivers (Soła, Skawa, Raba, Dunajec, Wisłoka, and San) are consequent and follow the general slope of the relief from south to north (Fig. 1). The region is characterised by a high density of river networks with minimal spatial variation. The average specific runoff ranges from 8 $dm^3 \cdot s^{-1} \cdot km^{-2}$ to over 50 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The upper sections of these rivers are predominantly situated in areas with relatively unaltered natural environments. However, the middle and lower reaches of the Carpathian rivers exhibit significant anthropogenic transformations, attributed to settlement expansion and a long history of river regulation, which has

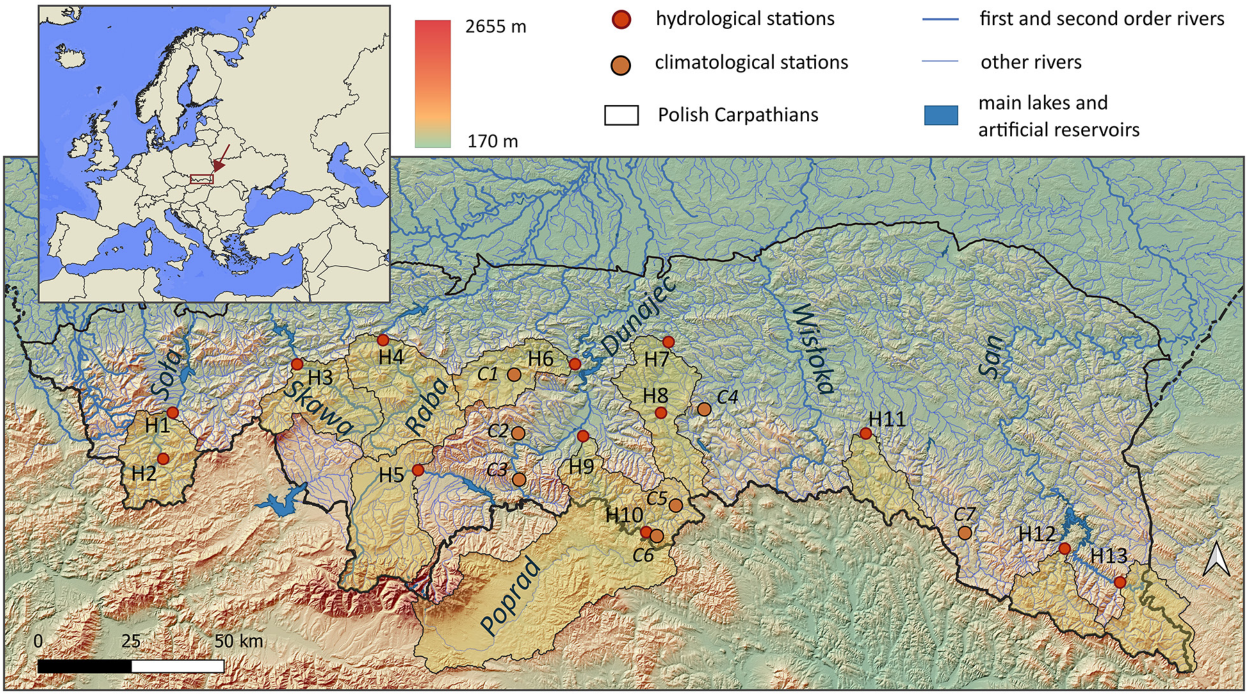

Fig. 1. Study area and locations of measurement points.

altered environmental characteristics, including hydrological conditions (Witkowski 2021). Such transformations are closely linked to river channel regulation and, most notably, to the construction and operation of dam reservoirs. The western portion of the Polish Carpathians is characterised by higher absolute and relative heights and higher precipitation totals than the Eastern Carpathians, largely due to an increase in continental climate features. Higher precipitation is also recorded in the Beskid catchments (relative to the foothills), whereas temperature is higher in catchments located in the foothills (Bochenek, Kijowska-Strugała 2022).

The hydrological regime of the rivers of the Polish Carpathians is characterised by high temporal and spatial variability and is described as unbalanced with a marked differentiation between the western and eastern portions of the area. Carpathian rivers are fed by precipitation, melting snowpack, and groundwater drainage. Flood surges occur in two seasons (spring and summer; Dynowska 1971). In the Carpathian region, a decrease in the duration and maximum thickness of snow cover has been noted in recent years (Kędzia et al. 2023). A shift to increasingly pluvial regimes of river flows has also been noted, especially during winter (Mostowik et al. 2019, Rajwa-Kuligiewicz, Bojarczuk 2024). This corresponds to a general trend observed in many mountain areas in Europe (Laghari et al. 2012, Hanus et al. 2021, Muelchi et al. 2021). The catchments show a recession of snowmelt recharge and an increase in the role of groundwater recharge (Bochenek, Kijowska-Strugała 2022, Siwek et al. 2022).

Data and methods

Two types of ice phenomena were chosen to analyse the ice regime transformations of the studied rivers: total ice cover (TIC) and border ice (BI). Together, these phenomena are collectively referred to as ice cover (IC) in this study. This approach was used to account for the fact that, in mountainous areas, the total IC is often discontinuous and formed from a combination of developing BI (Beltaos 2013). Data on the occurrence of IC during the period 1980–2020 at 13 water gauge cross sections (H1–H13) were obtained from the online resources of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI 2024) and hydrological yearbooks published by the same organisation. Water gauge cross sections located on seminatural rivers were specifically chosen to ensure that climatic conditions were the primary factors influencing transformations in ice conditions (Fig. 1).

Subsequently, data quality analysis was performed by comparing the IC occurrence dataset with information on the daily activities of observers at the water gauge cross-sections. Data on observers' working dates were obtained from IMWM-NRI (2024). It was assumed that if an observer conducted measurements at a given cross-section on a specific day, the IC occurrence data for that day should be considered reliable. Minor gaps in data were supplemented by information from the nearest water gauges.

Daily discharge data for the 13 water gauge cross sections (H1–H13) covering the period 1980–2020 were also retrieved from IMWM-NRI (2024) resources. Daily water temperature data for four water gauges (H4, H5, H8, and H9) were also obtained for different periods (H4: 1981–2020, H5, H8, and H9: 1984–2020). To examine climatic conditions during the study period (1980–2020), data for monthly average air temperature were obtained from the Climatic Research Unit gridded Time Series (CRU-TS; Harris et al. 2020). Data were acquired from the grid pixels within which hydrological stations H1–H13 were located. In addition, daily average air temperature data for the period 1980–2020 from seven climatological stations (C1–C7; Fig. 1) were obtained from IMWM-NRI (2024).

The non-parametric Mann–Kendall test (Mann 1945, Kendall 1975) was employed to detect trends within the acquired data series. Three thresholds of statistical significance were analysed: $p < 0.01$ (very strong evidence), $p < 0.05$ (strong evidence), and $p < 0.1$ (possible trend). However, the interpretation of these results considered the entire range of p-values, with lower values indicating stronger evidence of a trend. Trends were not ruled out if p-values did not fall below the specified thresholds, which is in line with contemporary practices in time series analysis and statistical research (Wasserstein, Lazar 2016, Wasserstein et al. 2019, Wang et al. 2020). Throughout this study, the results of the original Mann–Kendall test are reported, but in the case of time series characterised by the presence of autocorrelation, modified tests and tests using a pre-whitening procedure were also considered when interpreting the results (Hamed, Rao 1998, Yue, Wang 2002, 2004). The magnitude of change was determined using the Theil-Sen estimator (Theil 1992, Sen 1968). To perform detailed analyses of changes in discharge at selected hydrological stations, the Moving Average over Shifting Horizon (MASH, Anghileri et al. 2014) time series filtering method was used. This method involves averaging values over the same blocks of days (the length of which is determined by the 'w' parameter), while the 'Y' parameter determines the number of years over which daily values were averaged. In these analyses, the value of the 'w' parameter was assumed to be 10 days, whereas the 'Y' parameter was assumed to be 10 years. Correlation analyses were conducted using Pearson's linear correlation coefficient (Asuero et al. 2006, Hauke, Kossowski 2011). For consistency, all analyses adhered to a hydrological year defined as beginning on 1 November and ending on 31 October, ensuring that each winter season was fully captured within a single year. The discussion includes both the obtained results and the methodological aspects of applying statistical techniques.

Results

During the period 1980–2020, IC occurred for an average of 55.5 days at the surveyed stations (Fig. 1). For the period 1980–2000, the average number of days with IC was 61.2, whereas for the period 2001–2020, it was 49.6 days. An increase in the number of days with IC was noted from west to east and from north to south in the study area. Analysis based on Sen's slope indicates the presence of a decreasing trend in the number of days with IC at the studied stations, with statistical significance at $p < 0.05$ identified at seven stations (Table 1). The average trend from all stations was −7.25 days per decade. The largest percentage changes in the period 2001–2020 compared to the period 1980–2000 were observed in November (average decrease of 79%) and February (average decrease of 19%), whereas the smallest changes were observed in January (average decrease of 4.7%). A percentage increase in the number of days with IC was also recorded at individual stations in December, January, and February (Table 1). When considering the entire winter period, at the surveyed stations, the number of days with IC decreased by 17.8% on average for 2001–2020 compared to 1980–2000. A transformation of the structure of ice phenomena was observed to manifest in a decrease in the frequency of TIC and an increase in the frequency of BI (Fig. 2). At stations in the eastern part of the study area, TIC occurred almost every year during the period 1980–2006; in contrast, it has formed sporadically since 2007. Late formation and earlier breakup of the IC were also recorded in the study area (Fig. 3). For the period 1980–2000, IC appeared on average 33 days and disappeared on average 121 days of the hydrological year. In contrast, during the period 2001–2020, it appeared on average 42 and disappeared on average 117 days of the hydrological year. A statistically significant (at the $p < 0.05$ level) upward trend (later formation) in the dates of IC appearance was noted for five stations, whereas a downward trend (earlier breakup) was noted for two stations. On average, at all stations studied (H1–H13), the IC formed 4.1 days later per decade and decayed 3.3 days earlier per decade during the period 1980–2020. Intensification of changes occurred after 2010 when the IC appeared much later in each year and disappeared much earlier.

During the period 1980–2020, the study area experienced an increase in the average air

Table 1. Trend (1980–2020) and percentage change in the number of days with ice cover during the period 2001–2020 compared to the period 1980–2000 by month.

Station code	% change in 2001–2020 compared to 1980–2000						Trend [days per decade]
	Nov	Dec	Jan	Feb	Mar	Winter	
H1	−94.9	−38.8	−23.5	−37.1	−30.0	−36.4	−11.1***
H2	−93.5	−30.3	−14.1	−25.2	−15.0	−25.8	−8.9**
H3	−54.3	0.7	16.6	5.0	15.7	4.9	−3.0
H4	−73.8	−9.6	4.4	−12.3	0.0	−7.0	−4.1
H5	−67.6	−5.3	−5.0	−14.9	−19.3	−13.1	−6.7*
H6	−84.5	−8.5	3.7	11.2	24.5	−0.6	−0.8
H7	−95.2	−28.1	2.8	−17.7	−1.4	−16.5	−5.0*
H8	−75.9	−29.8	−5.3	−34.5	−20.8	−25.4	−9.0***
H9	−96.6	−33.7	−8.7	−27.1	−42.7	−27.2	−8.5**
H10	−83.3	−24.9	−10.9	−21.8	−32.5	−23.0	−11.3***
H11	−80.7	5.9	−2.3	−29.2	−2.3	−14.2	−4.9
H12	−67.3	−23.4	−13.0	−29.8	−32.1	−27.0	−11.4***
H13	−61.0	−12.9	−5.9	−17.7	−39.5	−20.4	−9.6***

Values that are statistically significant at the $p < 0.01$ level (very strong evidence) are marked with three asterisks (***), at the $p < 0.05$ level (strong evidence) with two asterisks (**), and at the $p < 0.1$ level (possibility of a trend) with one asterisk (*).

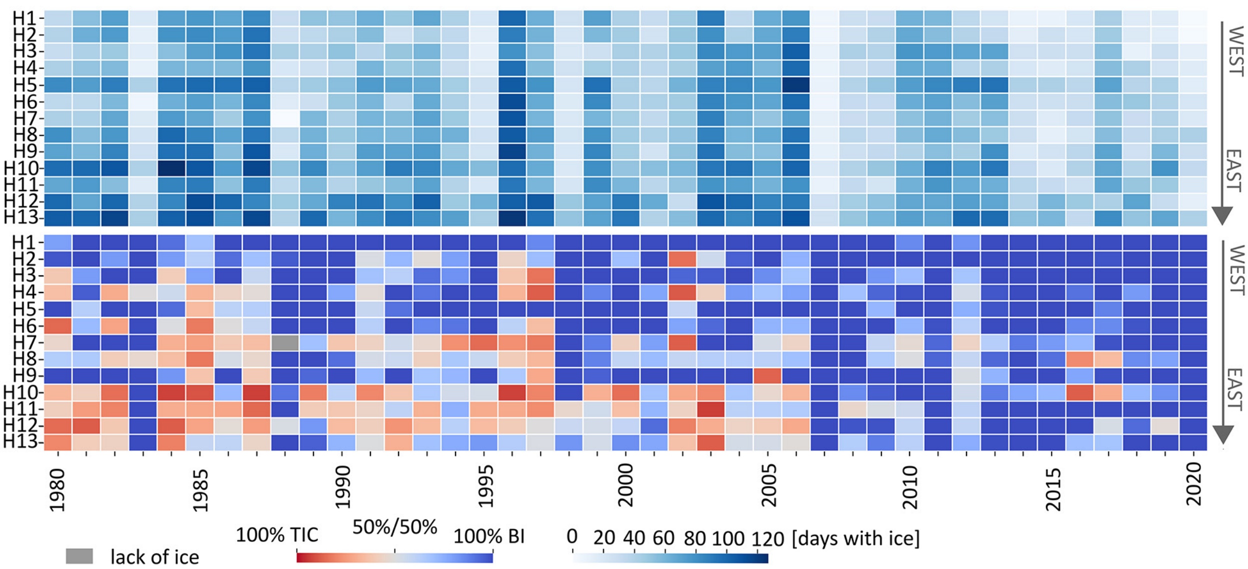

Fig. 2. Number of days with ice cover (IC) at each station (top panel) and the ratio of the share of total ice cover (TIC) and border ice (BI) in the sum of days with ice cover (bottom panel).

temperature during the winter period (Table 2). Sen's slope suggests the presence of an upward trend in all months. According to the CRU-TS database, the largest increases in average air temperature occurred in November (0.76°C per decade) and February (0.63°C per decade), but it should be noted that statistically significant values at the $p < 0.05$ level were recorded only for November and the entire winter period. The weakest (and not statistically significant at the $p < 0.05$ level) upward trend was in January (0.21°C per decade). CRU-TS data confirm direct measurements at climatological stations (C1–C7). In these cases, the most significant trends also occurred during November (average 0.77°C per decade) and February (average 0.71°C per decade), whereas the weakest trends occurred in January (average 0.29°C per decade). Also, for the measurement series from the stations, statistically significant trends at the $p < 0.05$ level were obtained only for November and the entire winter period. However, at the $p < 0.1$ significance level, significant trends were also recorded at three stations in February. Reductions in the number of days with air temperatures below 0°C were also recorded at the stations studied (data not shown). The largest decreases, as determined by Sen's slope, occurred in February (a decrease of 1.5 days per decade) and November (a decrease of 1.2 days per decade), whereas the smallest decreases occurred in December and January (a decrease of 0.6 days per decade). On average, the number of days with temperatures below 0°C in winter decreased by 4.75 days per decade at the surveyed stations during the period 1980–2020.

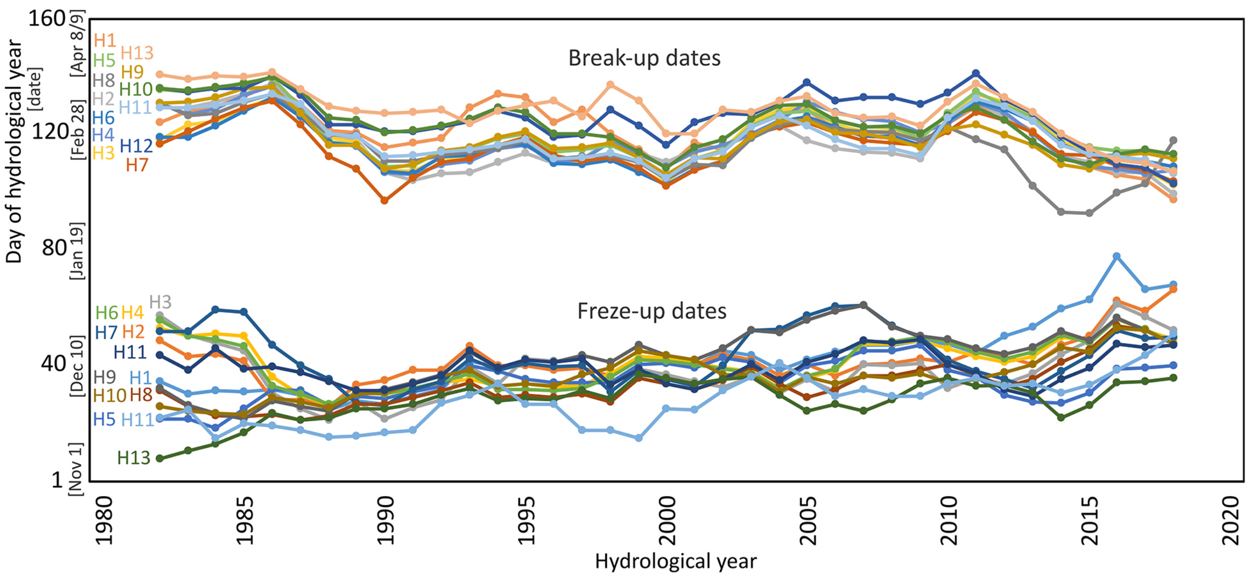

Fig. 3. Moving averages (5-year window) of dates on the first and last days of ice cover occurrence (sums of total ice and border ice).

Table 2. Trends in average air temperature over the period 1980–2020 in the study area.

Station code/ dataset	Trend [°C per decade]					
	Nov	Dec	Jan	Feb	Mar	Winter
CRU-TS	0.76***	0.40	0.21	0.63	0.62*	0.47**
C1	0.87***	0.34	0.16	0.69	0.44	0.41*
C2	0.55**	0.26	0.10	0.61	0.23	0.31
C3	0.74**	0.40	0.21	0.68	0.24	0.40*
C4	0.71*	0.13	0.50	0.92*	0.40	0.47**
C5	0.79***	0.19	0.23	0.64	0.21	0.37**
C6	0.85***	0.43	0.44	0.67*	0.38	0.49**
C7	0.85***	0.44	0.38	0.76*	0.26	0.49**

Values that are statistically significant at the $p < 0.01$ level (very strong evidence) are marked with three asterisks (***), at the $p < 0.05$ level (strong evidence) with two asterisks (**), and at the $p < 0.1$ level (possibility of a trend) with one asterisk (*).

As a result of the increase in air temperature, water temperature also increased at four hydrological stations (Table 3). The largest trend in water temperature at all stations was recorded in November (an average of 0.85°C per decade), which is similar to the increase in air temperature (an average of 0.77°C per decade). In contrast, the smallest increases in water temperature, or the absence of a trend, occurred in January (average increase of 0.06°C per decade) and February (average increase of 0.13°C per decade). In January, trends were statistically insignificant at most stations; however, at one station, Sen's slope indicated a decrease in water temperature. On average, for the entire winter period in the 1984–2020 multi-year period, water temperature increased by an average of 0.41°C per decade (at three stations: H5, H8, and H9). The average monthly water temperature is strongly correlated with the number of days with IC. For example, in February, the linear correlation coefficient between the average monthly water temperature and the number of days with IC at four stations ranged between −0.63 and −0.77, with an average of −0.68.

A strong relationship was also observed between discharge and the number of days with IC at the studied stations. In February, Pearson's linear correlation coefficient between the number of days with IC and discharge ranged from −0.51 to −0.80, with an average value of −0.65, indicating a robust negative correlation between these variables. Generally, low discharge consistently coincided with months characterised by a substantial number of days with IC in the studied catchments. Trend analysis of flow volumes, based on Sen's slope estimates (Table 4) and visual inspection of graphs generated using the MASH filtering method (Fig. 4), revealed a general increase in flow volumes across most of the studied water gauge cross sections during the winter period over the 40-year study period (Table 4). On average, flow volumes at the studied stations increased by 0.4 m^3 per decade throughout the

Table 3. Trends in water temperature at gauging stations.

Station code	Trend [°C per decade]					
	Nov	Dec	Jan	Feb	Mar	Winter
H4	1.00***	0.09	−0.06	0.00	0.03	0.22***
H5	0.76***	0.47***	0.22**	0.27**	0.39**	0.46***
H8	0.80***	0.26*	0.06	0.16**	0.29*	0.34***
H9	0.85***	0.37***	0.04	0.10*	0.66***	0.42***

Values that are statistically significant at the $p < 0.01$ level (very strong evidence) are marked with three asterisks (***), at the $p < 0.05$ level (strong evidence) with two asterisks (**), and at the $p < 0.1$ level (possibility of a trend) with one asterisk (*).

Table 4. Trends in discharge at gauging stations.

Station code	Trend [$m^3 s^{-1}$ per decade]					
	Nov	Dec	Jan	Feb	Mar	Winter
H1	0.80	0.19	0.45	1.33**	0.90	0.73**
H2	0.14	−0.15	0.05	0.72**	0.23	0.14
H3	0.15	−0.09	0.09	0.82	0.17	0.20
H4	0.13	−0.16	0.26	1.62**	−0.31	0.11
H5	1.08*	0.11	0.47	1.17**	0.55	0.74**
H6	−0.01	−0.18	−0.22	0.32	−0.60	−0.23
H7	0.04	−0.17	−0.19	0.89**	−0.65	−0.03
H8	0.04	0.02	−0.03	0.55**	−0.28	0.03
H9	1.42	0.05	0.69	2.68**	1.10	1.24*
H10	1.14*	0.20	0.43	1.83***	0.68	0.98**
H11	0.00	−0.25	0.15	0.82**	−0.07	0.20
H12	0.23	−0.16	0.78*	0.93**	0.74	0.55*
H13	0.73	0.12	0.77*	1.53**	1.43*	1.09***

Values that are statistically significant at the $p < 0.01$ level (very strong evidence) are marked with three asterisks (***), at the $p < 0.05$ level (strong evidence) with two asterisks (**), and at the $p < 0.1$ level (possibility of a trend) with one asterisk (*).

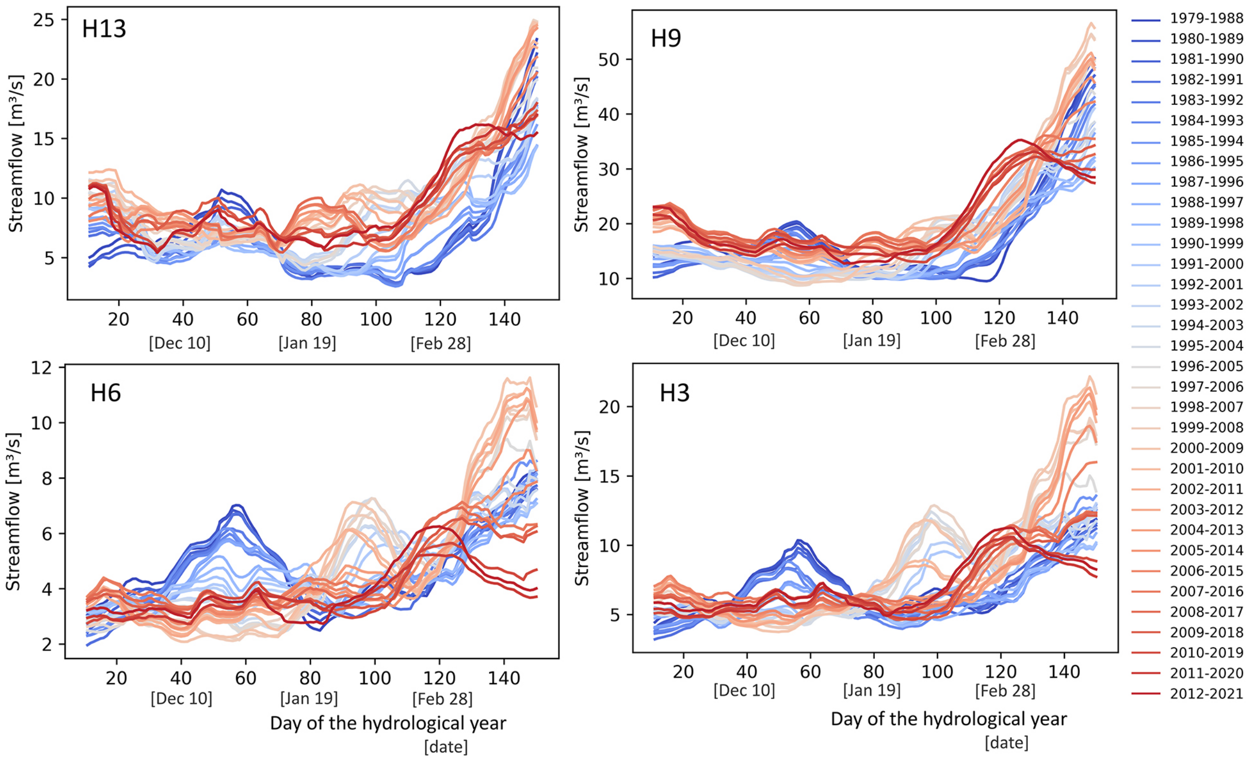

Fig. 4. Time series of streamflow at selected stations filtered using the MASH method for the period 1980–2020.

winter season, with statistically significant trends recorded at four stations (at the $p < 0.05$ level). The most pronounced increases in flow volume were observed in February, with an average increase of 1.1 m³ per decade. During February, only two stations (H3 and H6) exhibited trends that were not statistically significant at the $p < 0.05$ level. Notably, these were also the only two stations at which an increase in the number of days with IC was recorded during the period 2001–2020 relative to the period 1980–2000 (Table 1). In contrast, the most ambiguous trends were observed in December, when changes were not statistically significant at the $p < 0.05$ level, and Sen's slope suggests significant variation in trends. Some stations showed a decrease in discharge.

Analyses of the graphs based on the MASH filtering method allow us to assume that a transformation of the temporal structure of outflow occurred in most studied catchments during the study period. This was manifested in the earlier occurrence of the spring flood and a general increase in flow volume, especially during the second half of the winter period (February). Several stations (e.g. H6 and H3) experienced a decrease in flow volume during the first half of the winter period (especially in December).

Discussion

Previous studies addressing the occurrence of ice phenomena in Carpathian rivers indicate a decline in ice frequency (e.g. Szczerbińska 2023, Kochanek et al. 2024) and a transformation in the structure of IC. This is reflected in a reduction in the occurrence of TIC and an increase in the frequency of BI (Wiejaczka 2011). In the study area examined herein, the temporal and spatial variability of IC is influenced by both meteorological factors and human activities. To date, research on the ice regimes of Carpathian rivers has primarily focused on the role of dam reservoirs in shaping river ice regimes (Cybreska 1975, Soja, Wiejaczka 2014, Fukś 2024, Fukś et al. 2024). Consequently, mechanisms driven by climatic conditions that lead to a decreased frequency of river IC in the region remain insufficiently explored. Herein, we selected hydrological stations along rivers where climatic factors are the primary determinant of ice phenomena, aiming to address this research gap.

This study has revealed that the disappearance of river IC in the seminatural catchments of the Polish Carpathians is a complex process influenced by various factors that interact in a heterogeneous manner over time. Considering only the winter period, the greatest increase in air temperature occurred in November, the month in which the first forms of IC appeared in Carpathian rivers before the increases in air temperature observed in recent decades (Gołek 1957). It should be noted that the rise in air temperature in Europe during the study period was not uniform. A significant shift occurred between 1987 and 1989, after which an upward trend in air temperature emerged. It is presumed that the appearance of the trend in this period was associated with a change in the frequency of mid-tropospheric circulation macrotypes (Marsz, Styszyńska 2023). Increased air temperatures in November resulted in a significant increase in water temperature, resulting in the disappearance of IC due to the limited possibility of water phase transformation. The warming of temperate rivers is supported by numerous studies, both from the Carpathian Mountains (Pekárová et al. 2011, Kędra, Wiejaczka 2018, Kędra 2020) and other parts of Europe (e.g. North et al. 2013, Jonkers, Sharkey 2016, Kędra, Wiejaczka 2018, Graf, Wrzesiński 2020). During the remaining months of the winter period, upward trends in water temperature were much smaller and often statistically insignificant, conditioned by smaller upward trends in air temperature and local conditions (Marszelewski, Pius 2016, Graf, Wrzesiński 2020, Kędra 2020). This suggests that, in the study area, the most significant transformations in the ice regime, driven by rising water temperatures, occurred at the beginning of the winter period, that is, during the initial stages of ice formation in rivers. These changes have led to the increasingly delayed formation of IC in the region, as confirmed by the findings of this and other studies (Szczerbińska 2023). Later river IC formation has also been reported for other mountainous areas in Europe, such as the Scandinavian mountains. Late freeze-ups and earlier breakups of up to a dozen days per decade over the period 1976–2005 have been reported there (Newton, Mullan 2021). This is particularly important given the often positive feedback relationship between ice formation and water flow velocity in riverbeds (Thellman et al. 2021). The initial formation of ice in the riverbed reduces flow velocity, which in turn facilitates the accumulation of more ice and the development of a stable IC (Stickler et al. 2010). Significant warming of water in November may hinder the formation of these initial ice forms (such as anchor ice), thereby influencing the subsequent development of the IC.

The study area showed a general upward trend in the volume of river flow during the winter. The largest increase in flow at the studied water gauges occurred in February and was found to correspond to an increase in air temperature. An increase in winter river flows has been recorded in many catchments of the Carpathian Mountains (Mostowik et al. 2019, Rajwa-Kuligiewicz, Bojarczuk 2024) and other mountainous areas (Laghari et al. 2012, Hanus et al. 2021, Muelchi et al. 2021). For example, Mostowik et al. (2019) identified an increase in average winter runoff (especially in January) and a decrease in autumn flow in the Bieszczady (Outer Eastern Carpathians) catchments. Other studies indicate a decrease in the proportion of flow caused by snowmelt in the Carpathian catchments and an increase in the importance of underground recharge during the winter (Bochenek, Kijowska-Strugała 2022, Siwek et al. 2022). The reasons for this increase in discharge during winter could be attributed to the progressive transformation of precipitation structure in the Carpathian region and the resulting increase in air temperature. As indicated by Kędzia et al. (2023), in the Tatra Mountains (the southern part of the present study area) during the period 1927–2020, no changes in monthly precipitation totals in winter periods were noted, whereas a significant decrease was observed in the share of solid precipitation (snow) in precipitation totals. There has also been a decrease in the annual number of days with snow cover above 1 cm (−1.9 days per decade) and a decrease in the maximum annual depth of snow cover (−1.8 cm per decade). As a result, the discharge of water from the catchment area into watercourses during the winter period has increased due to reduced retention in the form of snow and an increase in liquid precipitation (Muelchi et al. 2021). Additionally, a significant increase in temperature at the beginning of the winter period can result in subsequent ground freezing, which causes an increase in groundwater recharge (Mostowik et al. 2019). An increase in the volume of river flow can significantly reduce the possibility of IC formation due to an increase in the energy and velocity of the flow and mechanical action on the ice forming at the water surface, either causing the IC to break up or hindering the development of BI into a TIC

(Bagnold 1966, Brown et al. 2023). It is generally accepted that the formation of IC is possible in river sections with flow velocities of <0.6 m s^{-1} (Ashton 1986). An increase in flow volume at the studied cross sections and an associated increase in water flow velocity can cause this limiting threshold to be exceeded, limiting the formation of stable IC and promoting other forms of river ice (Lind et al. 2016). Earlier river IC breakup is observed in many areas of the Earth, including mountainous areas (e.g. Chen, She 2020, Newton, Mullan 2021). Batima et al. (2004), based on an observational series of varying lengths (mainly the second half of the 20th century), noted an earlier breakup of IC on rivers flowing from the mountainous regions of Mongolia, occurring 5–30 days earlier. At the stations used in this study (H1–H13), smaller upward trends in flow volume (or lack thereof) by month tend to correlate with smaller percentage decreases (or increases) in the number of days with IC between the two periods analysed. For example, stations H6 and H3 (Outer Western Carpathians) exhibited a decrease in flow volume in the first half of the winter period between 1980 and 2020, and no increase in the second half. At these stations, an increase in the number of days with IC from January to March during the period 2001–2020 was noted relative to the period 1980–2000. Another example is station H4 (Outer Western Carpathians), where no increase in water temperature was observed during the second half of the winter (January–March). Simultaneously, a significant increase in flow volume was observed in February, and no clear trend was observed in March. In this cross-section, a decrease in the number of days with IC was identified in February, whereas no significant changes were observed in March, indicating the important role of flow in the formation of river ice conditions.

The use of multiple thresholds of statistical significance in the Mann–Kendall test, coupled with the analysis of the entire spectrum of *p*-values, allowed for a more comprehensive assessment of the occurrence of trends in data series. Concerns about using simple statistical tests to detect trends in hydrological data series have been noted by many authors (e.g. Soja 2002, Hamed 2008, Wang et al. 2020), who emphasise that due to the complexity of natural processes, simple statistical tests can lead to inconclusive results. In the Carpathian region, a lack of statistical significance in the trends of flow volume is a typical phenomenon, with a clear predominance of certain trends (in the case of the winter period, increasing), which indicates the presence of general regularities. Such trends cannot go unnoticed, as they can indicate a uniform direction of change throughout the study area, despite the lack of statistical significance at $p < 0.05$. The analysis of the entire spectrum of *p*-values considered in this article, supported by additional methods of analysis (e.g., charts based on smoothing with the MASH method), allows a comprehensive assessment of changes in the hydrological regime. This holistic approach to analysing hydrological data is consistent with contemporary general approaches to statistical analysis. The statistical community indicates that one should not take the *p*-value as the only indicator of the presence or absence of an effect, which is unfortunately a common practice (Wasserstein, Lazar 2016, Wasserstein et al. 2019).

The results presented here indicate that changes in river water temperature and increases in river flow are important factors influencing the ice regime of the studied mountain rivers. These factors interact heterogeneously over time: during the first half of the winter (especially November), the increase in water temperature is more marked, whereas in the second half (especially February), an increase in flow volume is observed. However, it should be noted that the formation of IC on small streams is a very complex process, conditioned by some natural and anthropogenic factors (Ashton 2011, Lind et al. 2016, Fukś et al. 2024). An increase in air temperature can indirectly affect other processes and phenomena, resulting in observed changes in the ice regime of rivers due to several interrelated changes in the natural environment. To understand in more detail the links between climatic variability and river ice regime changes, it is necessary to conduct further scientific research based on more detailed measurements and observation data and through the application of advanced statistical methods.

Conclusions

This study examines the relationship between the occurrence of IC on seminatural Carpathian rivers and the long-term variability of air temperature, water temperature, and flow volume. The main conclusions of the study are as follows:

1. In the study area, during the period 1980–2020, a decrease in the frequency of IC was observed, reaching 7.25 days per decade. The most changes in the study period were recorded in November and February. Trends were also observed in the dates of IC formation (by an average of 4.1 days per decade later) and disappearance (by an average of 3.3 days per decade earlier). Additionally, there was a noticeable increase in the share of BI occurrence in the total number of days with IC.
2. At the beginning of the winter period (November), the disappearance of IC occurrence is mainly conditioned by an increase in water temperature (by an average of 0.85°C per decade). This limits the development of ice phenomena at the stage of IC formation by delaying the formation of the initial ice forms.
3. In the middle of the winter period (especially February), the decrease in the incidence of IC is largely due to the increase in the volume of flow of the studied rivers (by an average of 1.1 m^3 per decade in February). This increase in flow volume makes it more difficult for BI to form (due to the increase in water flow velocity) and causes mechanical breakup of IC.
4. Both the increase in water temperature and the increase in flow volume during the winter period occur as a result of the increase in air temperature. During the period 1980–2020, the increase in winter air temperature in the study area averaged 0.47°C per decade (based on the CRU-TS database). Measurements from climatological stations confirm these results. The largest increases in average air temperature occurred in November (0.76°C per decade) and February (0.63°C per decade), which translated into the most changes in the river ice regime in these months. However, it should be noted that a statistically significant trend at the $p < 0.05$ level was recorded only for November and the entire winter period.
5. Analysis of the entire spectrum of p-values in the Mann–Kendall test, supported by other analytical methods (smoothing by the MASH method), allows a comprehensive assessment of the occurrence of trends in hydroclimatic data on river IC. Adopting a single threshold p-value on the basis of which the presence or absence of a trend is decided can lead to erroneous conclusions.

Financial support

This research was funded in whole by the National Science Centre, Poland (grant no. 2020/39/O/ST10/00652).

Author contributions

MF and ŁW conceptualised the study and wrote the manuscript. MF acquired the data, conducted the analysis, and visualised the results.

Acknowledgments

The authors would like to thank the anonymous reviewers for their valuable comments on an earlier version of the manuscript.

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