https://doi.org/10.5194/egusphere-2026-6596
Preprint. Discussion started: 4 November 2026
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Patterns and drivers of long-term changes in ice phenomena along the Vistula River (Central Europe)

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Abstract

Changes in river ice regimes are evolving rapidly in response to climate warming, and local anthropogenic influences may further modify their spatial and temporal variability. However, both the combined and individual effects of climate change and human activities on river ice phenomena remain poorly understood, particularly at the scale of entire river systems. In this study, we investigated long-term changes in river ice occurrence along the entire course of the Vistula River during the period 1950–2025, using hydrological observations from 54 gauge stations, Landsat satellite imagery and ERA5 climate reanalysis data. The results revealed a significant increasing trend in mean winter air temperature of 0.42 °C per decade, accompanied by decreases in both freezing degree days and the number of frost days. Concurrently, the frequency of river ice phenomena along the Vistula River decreased at an average rate of 6.2 days per decade, while the mean annual number of days with river ice phenomena declined from 49.4 in 1950–1985 to 26.5 in 1986–2020. Satellite observations further showed an average 17.7 percentage points decrease in river ice extent between the periods 1985–2005 and 2006–2025. Despite the overall declining trends on the whole-river scale, the spatial distribution of river ice phenomena exhibited pronounced heterogeneity. River reaches subject to the least human disturbance were characterized by the most frequent river ice occurrence and the strongest relationship with air temperature. In contrast, reaches heavily affected by reservoirs, thermal and chemical pollution, saline mine water discharge, urban areas, and channel regulation exhibited a substantially weaker relationship between ice occurrence and air temperature. Overall, these findings indicate that the Vistula River's contemporary ice regime is shaped by the combined effects of climate warming and local anthropogenic pressures. Although climate change determines the broader direction of long-term decreases in river ice phenomena, human activities substantially modify their spatial patterns, highlighting the need to account for anthropogenic influences when assessing the response of river ice regimes to ongoing climate change.

Keywords: river ice regime; climate change; anthropogenic impacts; remote sensing; Landsat; ERA5

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1. Introduction

River ice phenomena play a crucial role in riverine ecosystem functions, geomorphological processes, and human activities. Ice within a river channel may lead to the formation of ice jams, potentially triggering extensive flooding and posing a threat to hydraulic infrastructure (Lindenschmidt et al., 2023). In northern regions, frozen rivers also serve as seasonal transportation and communication routes (Brown et al., 2018). Additionally, river ice regimes influence habitat conditions for aquatic organisms, food web functioning, and biogeochemical processes, shaping aspects including microbial community structure and water quality (Cruaud et al., 2020; Thellmann et al., 2021). River ice phenomena also modify morphogenetic processes, including sediment transport and bank erosion (Chassiot et al., 2020).

River ice phenomena have changed significantly since the mid-twentieth century due to ongoing climate change and increasing anthropogenic pressure (Fukś, 2023). The main climatic driving factor is increasing winter air temperature, reflecting the growing accumulation of energy within the climate system (Masson-Delmotte et al., 2021). These rising air temperatures primarily affect river ice by increasing river water temperatures and altering flow dynamics (e.g. Liu et al., 2022; Fukś and Wiejaczka, 2025a). Consequently, river ice forms later, breaks up earlier, and persists for shorter periods (e.g. Marszelewski and Pawłowski, 2019; Fukś, 2023; Szczerbińska and Siwek, 2025). A decrease in river ice extent has also been documented (Yang et al., 2020). River ice phenomena are also strongly influenced by human activities, including chemical and thermal pollution (Takács et al., 2013), reservoir operation (Fukś et al., 2024; Fukś and Wiejaczka, 2025b), river channel regulation (Takács et al., 2013; Pawłowski, 2015), and intentional ice-breaking to reduce flood risk (Lindenschmidt et al., 2023).

Due to the numerous interacting factors influencing river ice phenomena, their temporal and spatial variability remains poorly understood. In particular, the effects of changes in climatic conditions and anthropogenic pressure on the ice regimes of individual reaches of long north–south-oriented rivers are poorly constrained. Previous studies have typically relied on a single data type (e.g., in situ observations) and focused on selected river reaches. Few studies have comprehensively assessed the temporal and spatial dynamics of river ice phenomena along entire river courses, particularly using multiple integrated data sources. Consequently, it remains unclear to what extent observed changes in river ice regimes are driven by climatic changes versus other anthropogenic influences.

Central Europe provides an ideal setting for investigating the spatiotemporal patterns of river ice phenomena, due to its location within the transitional zone between oceanic and continental climatic influences. This results in high variability in winter thermal conditions and substantial differences in the frequency, intensity, and duration of river ice phenomena. The region is also characterized by strong and spatially varying anthropogenic pressure and a protracted history of hydrological modification. Contemporary river systems in Central Europe have been extensively altered, including channel regulation, reservoirs and hydropower plant construction, catchment urbanization, and land-use change (e.g. Belletti et al., 2020; Maaß et al., 2021; Habersack and Bradley, 2022; Havlíček et al., 2022). These modifications substantially alter river hydrological

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regimes and affect the functioning of riverine ecosystems (e.g., Rottler et al., 2020). Overall, these characteristics provide a unique opportunity to investigate the combined influence of natural and anthropogenic drivers on river ice regimes.

The Vistula River is a particularly valuable case study for investigating river ice variability due to its significant length, north–south orientation, and the highly diverse climatic, hydrological, and morphological conditions throughout its catchment, caused by its location within the transitional zone between oceanic and continental climatic influences. Additionally, this river's variable anthropogenic pressure, including channel regulation, hydraulic infrastructure, and river valley development, provides an opportunity to assess the relative importance of climate change and human activity in shaping the contemporary river ice regime (Majewski, 2013; Marszelewski, 2017; Niemirycz, 2018). Previous studies of river ice phenomena on the Vistula have focused primarily on selected river reaches, including investigations of the upper Vistula and its tributaries (e.g. Łajczak, 1991; Fukś and Wiejaczka, 2025b; Szczerbińska and Siwek, 2025), focused on the characteristics and controls of river ice processes, and studies of the lower Vistula (e.g. Grześ, 1991; Achrem and Gierszewski, 2007; Pawłowski, 2017), which analyzed the drivers of river ice variability, with a focus on ice jams and their hydrological consequences. However, despite this extensive research, comprehensive studies examining the spatiotemporal variations in river ice phenomena along the entire course of the Vistula over a multi-decadal period are still lacking.

This study's main aim is to comprehensively assess the temporal and spatial variability of the Vistula River's ice regime. To achieve this, our objectives are to: (1) identify the key factors driving changes in the Vistula River ice regime; (2) determine the river reaches with the greatest and least alteration of the ice regime; (3) assess the relative importance of climate change and anthropogenic pressure in shaping river ice processes; and (4) evaluate the spatial variability of the river's ice regime response to natural and anthropogenic drivers.

2. Study area

The Vistula River flows through varied topography, ranging from mountainous areas through uplands and basins to extensive lowlands, each characterized by distinct climatic, hydrological, and morphological conditions. The Vistula catchment lies within the temperate transitional climate zone between oceanic and continental influences, resulting in highly variable winter thermal conditions and pronounced temporal and spatial variability in river ice and thermal processes. Consequently, the Vistula basin is a model example of a Central European river system, due to both its paleogeographic development and contemporary hydrological and geomorphological processes (Starkel, 2001).

The Vistula River is conventionally divided into three sections (upper, middle, and lower), each characterized by distinct hydrological and morphological features that influence thermal and ice processes (Fig. 1). The upper Vistula comprises the river's Carpathian and Subcarpathian sections, extending from its headwaters (located at an elevation of ~1100 m a.s.l.) to its confluence with the San River. This section is 385.9 km long, representing 36.8% of the total length of the Vistula. It is characterized by a pronounced longitudinal gradient, particularly in the Carpathian reach, and by a gradual downstream decrease in channel sinuosity (Łajczak et al., 2021). Along this section, the Vistula typically comprises single-thread, sinuous,

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or meandering channels. The mean discharge increases from approximately 6 m³ s⁻¹ at station S1 to around 450 m³ s⁻¹ downstream of the San confluence (station S22; Fig. 1). The middle Vistula begins at the confluence with the San River and flows northward across the Polish Uplands before turning northwest towards the Warsaw Basin, ending at the confluence with the Narew River (station S34; Fig. 1).

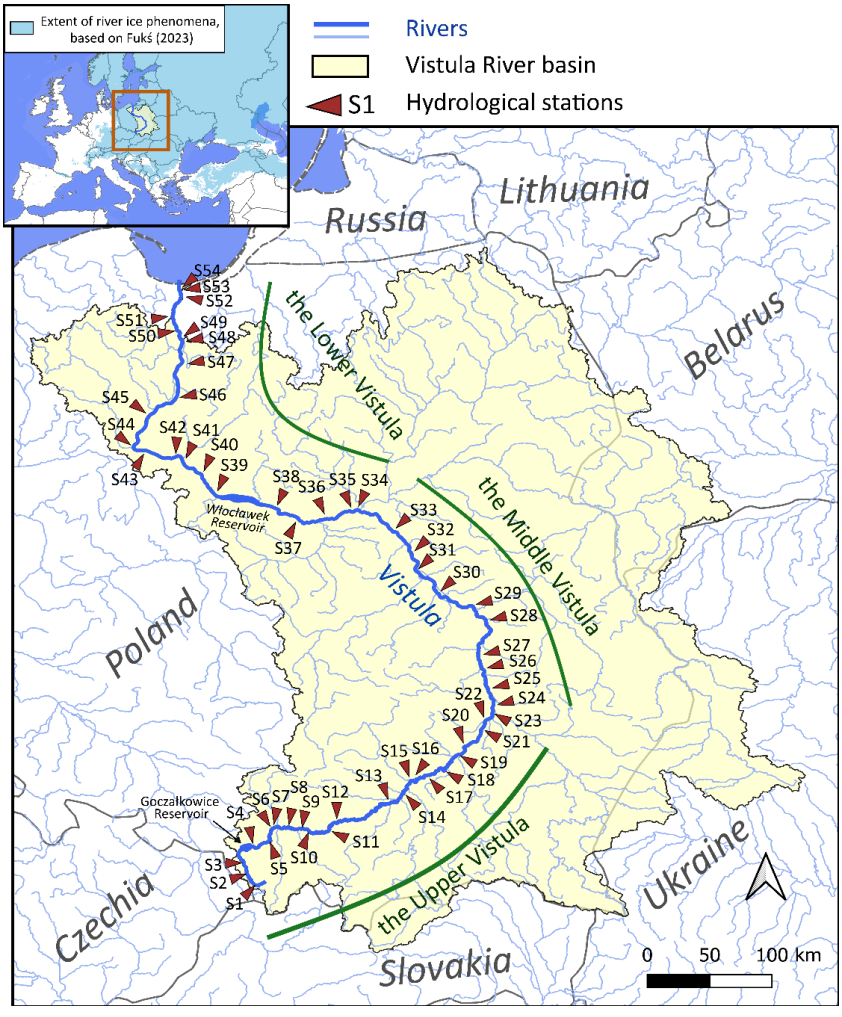


Figure 1. Map showing the Vistula River Basin and the locations of the studied hydrological stations.

This section is 270.3 km long, accounting for 25.8% of the river's total length. The channel gradient decreases from approximately 0.28‰ to less than 0.2‰. The mean discharge is approximately 575 m³ s⁻¹ in Warsaw (station S33) and increases to ~950 m³ s⁻¹ downstream of the confluence with the Narew River (station S34). A characteristic feature of the middle Vistula is its braided channel pattern, including numerous mid-channel and lateral sandbars.

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The lower Vistula extends for 391.3 km, representing 37.4% of the total river length. Along this section, the longitudinal channel gradient gradually decreases to approximately 0.1‰. Between the confluence with the Narew River and Płock (stations S34–S38), the river flows through multiple interconnected channels, forming an anabranching channel pattern (Łajczak et al., 2021). Downstream of this reach, the Vistula returns to a single-thread channel, although locally braided reaches with numerous sandbars are still present. The mean discharge at the river mouth section in Tczew (station S51) is approximately 1080 $m^3 s^{-1}$. The final 200 km of the Vistula has been extensively regulated. Given the marked spatial variability in discharge, channel morphology, and climatic conditions along the river, substantial differences in the spatial patterns of water temperature and river ice processes are likely.

Various forms of anthropogenic pressure occur along the entirety of the Vistula River, including channel regulation, hydraulic infrastructure, reservoir operation, water abstraction, industrial and mining activities, and intensive river valley development. It is estimated that wastewater from more than 100 industrial facilities is discharged into the Vistula. Collectively, these factors variably modify flow conditions and river ice formation, evolution, and decay, resulting in pronounced spatial variability of the river's ice regime. Several reservoirs are located along the Vistula River, the largest of which is the Włocławek Reservoir, with a storage capacity of ~400 million m^3, a surface area exceeding 70 km^2, and a mean depth of 5.5 m. Commissioned in 1970, this reservoir has substantially altered river ice conditions both upstream and downstream of its dam (Grześ, 1991; Pawłowski, 2017). The upper Vistula also includes the Goczałkowice Reservoir, which began operating in 1956. This reservoir has a mean depth of 5.3 m and a total storage capacity of 168 million m^3. Additionally, in the headwaters of the Vistula, the small Wisła Czarne Reservoir, commissioned in 1973, has a storage capacity of 4.5 million m^3 and a mean depth of approximately 13 m. Overall, the combination of a gradient in natural conditions and varying anthropogenic pressure within a single river system provides a unique opportunity to assess the relative importance of climate change and human activities in shaping changes in the river's ice regime.

3. Data and methods

To investigate the temporal and spatial variability of river ice phenomena along the Vistula River, we used data from multiple complementary sources. River ice occurrence data for 1949–1981 were obtained from the Hydrological Yearbooks of Surface Waters – Vistula (1949–1981), published by the Polish State Institute of Hydrology and Meteorology (until 1970) and subsequently by the Institute of Meteorology and Water Management (from 1971 onwards). As these yearbooks were available only in printed form, the daily observation records of individual river ice phenomena were manually digitized onto a digital database. River ice occurrence data for 1981–2020 were obtained from the online database of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI; https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/, accessed: 7 July 2026). The two datasets were harmonized using the following river ice phenomena classes: total ice cover, border ice, frazil ice, ice floe, and ice jams. The annual number of river ice days was calculated as the total number of days on which at least one type of river ice phenomenon

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was recorded. The compiled dataset was subjected to quality control to assess its completeness and identify potential gaps. To do so, observation schedules from IMWM-NRI were cross-checked against the compiled database. Where water level data were available and the observation schedule confirmed that measurements had been conducted, both recorded ice occurrence and absence were treated as valid observations. In total, river ice observations from 54 hydrological stations were compiled; however, only 18 stations provided complete or near-complete records spanning the entire 1950–2020 period, whereas the remaining stations provided observations for only part of the study period. Only stations with at least 10 years of observations were included in the analyses. Spatial analyses of river ice occurrence were based on data from all 54 hydrological stations, with missing observations supplemented using records from the nearest available stations. Analyses of temporal variability were restricted to the 18 stations with no significant gaps in the observation record (defined as >10% missing data), although data gaps at four of these stations were also filled using observations from the nearest neighboring stations.

Based on data from 54 hydrological stations, the mean annual numbers of days with individual river ice phenomena were calculated for consecutive 10-year periods for the different sections of the Vistula River. In all the analyses, the hydrological year, defined as 1 November to 31 October, was adopted as the basic temporal unit to ensure each winter season (November to March) was contained within a single study year. Based on a review of the literature, the main factors potentially affecting river ice processes were identified, and their locations are indicated in Fig. 4.

Temporal variability in river ice occurrence was analyzed using data from 18 hydrological stations. First, long-term trends for the whole study period (1950–2020) were estimated using the Theil–Sen estimator (Hussain et al., 2019). The statistical significance of the trends was assessed using the non-parametric Mann–Kendall test (Hussain et al., 2019). A significance level of $p < 0.05$ was adopted, while p-values were also interpreted continuously, with lower values indicating stronger evidence against the null hypothesis. Subsequently, the mean annual numbers of days with any river ice phenomenon and those with complete ice cover were calculated for two sub-periods: 1950–1985 (A) and 1986–2020 (B). The difference between the mean values for the two sub-periods was also determined, and the statistical significance of these differences was evaluated using the non-parametric Mann–Whitney U test (Mann and Whitney, 1947). The null hypothesis assumed identical distributions in groups A and B, while the alternative hypothesis assumed they differed. These methods enabled the quantification of both the direction and the magnitude of changes in river ice occurrence.

To assess and visualize long-term trends and temporal variability, we applied the Moving Average and Running Trend Analysis (MARTA) method (Ranzi et al., 2024; Fukś and Wiejaczka, 2025b). This approach involves calculating moving averages and trend estimates for all possible sub-periods of a time series longer than 10 years, with the results displayed as triangular MARTA diagrams (Ranzi et al., 2024). In these diagrams, the vertical axis represents the length of the analyzed sub-period, while the horizontal axis indicates its central year. Trends were estimated using the Theil–Sen estimator, and their statistical significance was assessed with the Mann–Kendall test. Trends significant at the $p < 0.05$ level are plotted with larger symbols. Statistically significant trends located in the upper part of the diagrams represent persistent long-term changes, whereas those in the lower part reflect short-term variability. MARTA diagrams enable the simultaneous analysis of variability and trends across multiple temporal scales and have been successfully applied in studies of river ice phenomena and other

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components of the cryosphere (Ranzi et al., 2024; Fukś and Wiejaczka, 2025b). These diagrams were prepared using the average values calculated from all 18 gauging stations and for subsets of stations in areas both directly and not directly affected by anthropogenic pressures.

To quantify the spatial and temporal changes in river ice extent, Landsat 5, 7, 8, and 9 satellite data were used. The imagery was obtained from the Collection 2 Tier 1 Top-of-Atmosphere Reflectance archive, which provides high geometric accuracy and radiometric consistency (Crawford et al., 2023). Data processing was performed using the Google Earth Engine cloud computing platform, enabling efficient analysis of large geospatial datasets (Gorelick et al., 2017). River ice extent was quantified using the approach described by Fukś et al. (2026, in press). In this method, a dynamic water mask was generated separately for each year to exclude mobile channel features (e.g., sandbars) that could potentially interfere with river ice detection. The annual water masks were generated using a combination of the JRC Global Surface Water dataset and Landsat imagery acquired during the low-flow period (August–October). First, only pixels with a long-term water occurrence exceeding 80% were retained as potential river areas. Subsequently, the median Normalized Difference Water Index (NDWI) was calculated for each year from all available cloud-free Landsat images acquired during the low-flow season. Pixels with median NDWI values below 0, corresponding to exposed depositional forms under low-flow conditions, were excluded from the final water mask. This procedure enabled the active water surface to be delineated for each studied year while also accounting for interannual changes in the position and extent of mobile channel features.

Subsequently, all available Landsat images acquired during the winter seasons of 1985–2025 with cloud cover below 30% were clipped to the calculated water masks representing the Vistula River. All images were subjected to cloud masking using the Quality Assessment band (QA_PIXEL; Zhu and Woodcock, 2012). In total, 404 Landsat scenes covering the entire Vistula River were obtained for the study period. Each image was classified into two classes (ice/no ice) using a random forest machine-learning algorithm. The training dataset consisted of pixel-level reflectance values and derived variables collected for the Vistula River (training dataset with description available at https://zenodo.org/records/20083432). Detailed descriptions of the classification model and Landsat processing workflow are provided by Fukś et al. (2026, in press). Their method, validated using 883 paired satellite and in situ observations from the Vistula River, demonstrated higher accuracy and spatial detail than previously applied methods. It achieved a balanced accuracy of 0.95 for total ice cover detection and 0.81 for detecting all river ice phenomena, with F1 scores of 0.89 and 0.65, respectively. In the present study, the ice classification results were used to calculate the proportion of river ice cover relative to the total water surface area for two sub-periods (1985–2005 and 2006–2025), both for the entire Vistula River and for successive river sections approximately 100 km in length.

A range of auxiliary datasets was used in the analysis. Climatic conditions during the study period were characterized using air temperature data from the ERA5 climate reanalysis dataset (Hersbach et al., 2020), including daily mean, minimum, and maximum air temperature at 2 m above the surface. Additional parameters were then derived from these data, including seasonal freezing degree-day sums and the number of days with mean air temperatures below 0 °C and −5 °C. These parameters were averaged for consecutive hydrological years, and the resulting time series were analyzed for trends using the Theil–Sen estimator and the Mann–Kendall test (Hussain et al., 2019). Water temperature variability was analyzed from 1984–2024 at

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six monitoring stations using data obtained from the online resources of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI; available at: https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/, accessed: 7 July 2026).

4. Results

4.1 Changes in winter thermal conditions along the Vistula River and their relationship with river ice phenomena

The analyses revealed a statistically significant increase in mean winter air temperature across the study area from 1950–2025, averaging 0.42 °C per decade ($p < 0.001$; Fig. 2). A decrease in the seasonal sum of freezing degree days was also observed, with an average decrease of 28.4 days per decade ($p < 0.001$) Similar decreases as were noted in the number of days with air temperatures below 0 °C (−4.6 days per decade; $p < 0.001$) and below −5 °C (−2.4 days per decade; $p < 0.001$). Figure 2 presents the temporal and spatial dynamics of air temperature changes.

The coldest decade during the study period was 1960–1969, with a mean winter air temperature of −1.05 °C. Slightly higher temperatures were recorded in 1950–1959 (−0.54 °C) and 1980–1989 (−0.15 °C). A marked shift in winter thermal conditions occurred during 1987–1989, when the stationary behavior of the air temperature time series was disrupted, and a significant increasing trend emerged. After 1990, each subsequent decade was characterized by successively higher air temperatures (0.70 °C, 0.91 °C, and 1.17 °C). Following 2019, an acceleration in the rate of winter air temperature increase was observed. During 2019–2025, the mean winter air temperature reached 2.71 °C. The observed winter air temperature increases during the study period are further supported by statistically significant increases in both mean minimum and maximum air temperatures. These increases ranged from 0.4 to 0.5 °C per decade (with statistically significant trends at all stations at $p < 0.05$) and averaged 0.43 °C per decade for both parameters.

Overall, these results indicate a substantial increasing trend in winter air temperatures across the study area from 1950 to 2025. Two major transition points can be identified within the time series: (1) 1987–1989, after which a statistically significant warming trend emerged, and (2) 2019, after which the rate of warming accelerated. These changes indicate a pronounced shift in winter thermal conditions during the study period, representing the primary climatic background controlling river ice processes.

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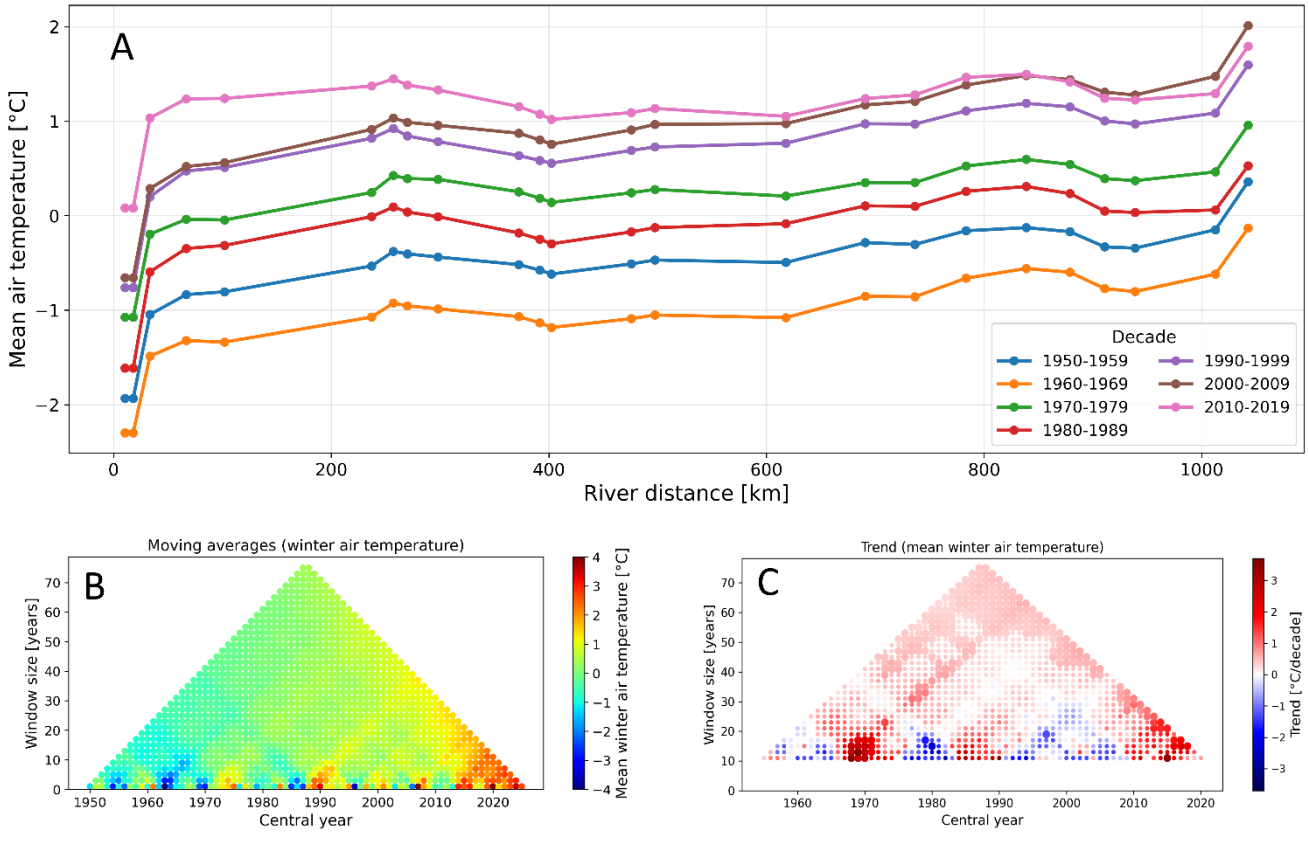


Figure 2. (A) Plot showing the average winter air temperature along the Vistula River, and MARTA diagrams showing (B) moving averages of winter air temperature and (C) mean winter air temperature trends.

To determine the Vistula River system's response to increasing air temperatures, changes in water temperature and river discharge were analyzed at selected monitoring stations. For the water temperature analysis, the longest available measurement series common to all stations was used, spanning 1984–2024. During this period, the mean winter water temperature increased along the entire longitudinal profile of the Vistula, with increases ranging from 0.1 to 0.8 °C per decade and an average increase of 0.42 °C per decade (based on data from six monitoring stations). Over the same period, a decrease was also observed in the number of days with water temperatures below 1.0 °C, ranging from 5 to 14 days per decade depending on the station, with statistically significant trends at the $p < 0.05$ level identified at five stations. In contrast, no consistent trends in river discharge were identified over the entire study period. Overall, the water temperature changes were consistent with the observed changes in air temperature, indicating the effective transfer of climatic signals into the river system.

The correlation analysis between the occurrence of river ice phenomena, river discharge, and air temperature revealed that ice occurrence was strongly negatively correlated with air temperature (Fig. 3). The strongest correlations between ice

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occurrence and air temperature were observed at gauging stations in the middle section of the Vistula River (350–500 km along the river's course). Pearson's linear correlation coefficient values between the monthly number of days with river ice phenomena and mean monthly air temperature ranged from −0.58 to −0.83. The lowest-magnitude correlation coefficient values (i.e., those indicating the weakest relationships) occurred in the upper Vistula section (first 60–260 km of the river course), with values of −0.67 and −0.58 at two stations. Notably, the river reaches exhibiting the strongest negative relationships between air temperature and river ice occurrence were identified as the least modified by human activity, while those with the weakest correlations were the most strongly affected by anthropogenic disturbance. The correlation between the monthly number of days with river ice phenomena and river discharge was considerably weaker, with Pearson's correlation coefficients ranging from −0.18 to −0.30. For this pair of variables, river reaches characterized by substantial anthropogenic modification also tended to exhibit weaker correlation coefficients.

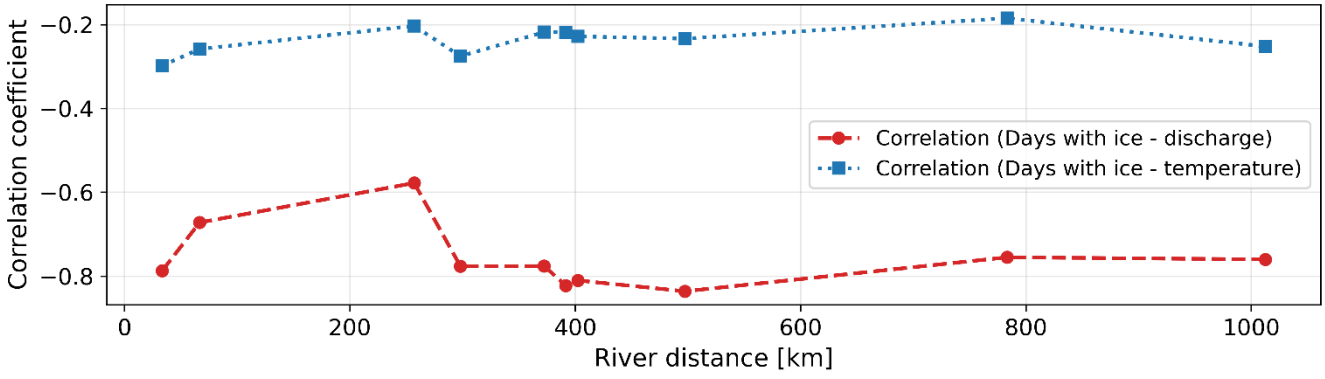


Figure 3. Plot showing linear correlation coefficients calculated along-river between the monthly number of days with ice phenomena and the mean air temperature and mean discharge.

4.2 Spatial variability in the occurrence of river ice phenomena along the Vistula River

The analyses revealed substantial spatial variability in the occurrence of river ice phenomena along the Vistula River (Fig. 4). In the upper section of the river (0–30 km), the mean annual number of days with river ice phenomena between 1950 and 2020 was approximately 32 days. In this mountainous (Carpathian) reach, total ice cover and border ice were the dominant forms, with frazil ice contributing only marginally. A gradual downstream decrease in the number of days with river ice phenomena was observed, associated with decreasing elevation (from over 500 to approximately 250 m a.s.l.) and a resulting increase in minimum winter temperatures. Despite the presence of the Wisła Czarne Reservoir, the river ice regime in this section remained largely undisturbed.

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Figure 4. Plots showing spatial and temporal variability of river ice phenomena along the course of the Vistula River, together with selected disturbing factors. Solid lines represent continuous sequences of the 54 gauging stations included in the analysis, while dashed lines indicate sections with interrupted continuity due to missing intermediate stations.

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In the next section of the Vistula River downstream (50–250 km; the area of the Subcarpathian basins), almost no river ice phenomena were recorded. This trend is attributed to multiple factors, including strong anthropogenic pressures disrupting river ice formation. The most prominent anthropogenic factors in this area include the inflow of warmer, highly mineralized mine waters from the Upper Silesian region, the operation of the large Goczałkowice Reservoir, pollutant emissions linked to industrial activity, and river channel regulation. These pressures have substantially altered the Vistula River's ice regime. However, a gradual recovery (i.e., renaturalization) of the ice regime is observed further downstream in the 250–370 km section. Here, the mean annual number of days with river ice phenomena increased from fewer than 10 to more than 30 days. This process is favored by the inflow of water from right-bank tributaries draining the Polish Carpathians, many of which have largely retained their natural hydrological characteristics. The inflow from the San River at ~380 km is particularly important, leading to a pronounced increase in the frequency of river ice phenomena observed downstream (Fig. 4). The mean number of annual days with river ice phenomena increases from approximately 33 days upstream of the San confluence (station S22) to approximately 43 days at downstream stations (stations S24 and S25). This increase may also partially result from the increasing continentality of the area's climate at more easterly longitudes. Along the 250–370 km section, complete ice cover and frazil ice were the dominant forms of river ice.

Further downstream, along the middle Vistula River section between 400 and 500 km, the ice regime is less affected by anthropogenic modification. This is evidenced by the high number of annual days with river ice phenomena (an average of 50 days between 1950 and 2020) and the limited number of potential disturbance factors. This section is characterized by frequent occurrence of total ice cover (an average of 23 days annually during 1950–2020), accompanied by frazil ice formation (an average of 18.8 days). These results suggest that this section represents the most natural part of the Vistula River in terms of river ice formation.

Further downstream, along the 500–620 km section of the middle Vistula River, a substantial decrease in the frequency of total ice cover was observed, from an average of 24.5 to 6.6 days. This decline was accompanied by an increase in the occurrence of border ice from 9.5 to 21.5 days annually and frazil ice from 19.9 to 22.1 days annually, resulting in no significant change in the total number of days with river ice phenomena. This section was characterized by the presence of several factors potentially affecting river ice processes, including chemical industry facilities, a coal-fired power plant, and the Warsaw metropolitan area.

Along the 620–780 km section of the lower Vistula River, a pronounced increase in the frequency of total ice cover was observed, reaching an average of 55 days annually during 1970–1979. This section was also characterized by a high number of days with other river ice phenomena, exceeding 80 days annually on average. The substantial increase in river ice occurrence was associated with the presence of the Włocławek Reservoir, commissioned in 1970, the largest reservoir of its type on the Vistula River. Reservoir operation promoted upstream ice-cover formation by reducing flow velocity and promoting frazil ice accumulation. Immediately downstream of the dam, the mean number of days with river ice phenomena decreased by

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approximately 10 days, and the number of days with total ice cover decreased by 30 days. Because of reservoir operation, total ice cover ceased to form along a several-kilometer section downstream of the dam.

The downstream section of the river (780–1047 km) is characterized by a low number of days with total ice cover (an average of less than 7 days per year during 1950–2020) and a relatively frequent occurrence of border ice (an average of 16 days per year during 1950–2020). A distinctive feature of the Vistula mouth section is the pronounced downstream increase in the frequency of ice floe occurrence, reaching an average of 52.8 days during 1950–1959. The high frequency of ice floe formation may be associated with icebreaking operations conducted on the lower Vistula and fluctuations in river water levels resulting from the operation of the Włocławek Reservoir.

The mean fraction of river ice cover (Fig. 5) during 1985–2025 (November–March), estimated from Landsat data, was 14.2%. The lowest values (10–11%) were recorded in the section downstream of the Włocławek Reservoir (765–865 km) and in the upper Vistula River (200–400 km). These reaches also exhibited the lowest frequency of river ice phenomena and total ice cover based on hydrological station observations. The limited ice extent in these sections results from anthropogenic pressures, primarily changes in the physicochemical properties of water caused by pollutant inputs in the 200–400 km section and the influence of the Włocławek Reservoir in the 765–865 km section. In contrast, the highest river ice proportions were observed in the 400–500 km and 700–765 km sections, reaching 17% and 21%, respectively. These observations likely resulted from the limited anthropogenic modification of the 400–500 km section and intensified ice cover development upstream of the Włocławek Reservoir in the 700–765 km section.

4.3 Temporal changes in the occurrence of river ice phenomena along the Vistula River

During the period 1950–2020, the frequency of river ice phenomena along the Vistula River decreased significantly (Fig. 5; Fig. 6). At all analyzed stations with continuous observation records (17 stations), the number of days with river ice phenomena decreased by an average of 6.2 days per decade. At 14 stations, the observed trends were statistically significant at the $p < 0.05$ level, whereas the changes at three stations were not statistically significant. The sharpest decreases, exceeding 9 days per decade, were observed at gauging stations located along the middle Vistula River (400–500 km section). In contrast, the weakest decreasing trends (<1 day per decade) occurred in areas with substantial anthropogenic influence in the upper Vistula River. This indicates a nearly continuous decrease in river ice frequency along the Vistula River with spatially varying rates of change.

The temporal structure of river ice occurrence reveals a distinct breakpoint in the stationarity of the time series during the mid-1980s (Fig. 6). During the first half of the study period (1950–1985), the mean annual number of days with river ice phenomena ranged from 11 to 73.5 days depending on the station, with an overall mean of 48.4 days (Table 1). In contrast, during 1986–2020, this range was 7.8 to 44.5 days, with an overall mean of 26.1 days. The average number of days with river ice phenomena decreased by 22.3 days between these two periods, and the change was statistically significant at 14 stations, as determined using the Mann–Whitney U test. Analogous changes were also observed for the total ice cover occurrence.

https://doi.org/10.5194/egusphere-2026-6596
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During 1950–1985, the mean annual number of days with total ice cover ranged from 3.8 to 37.8 days, with an overall mean of 17.9 days. During 1986–2020, these values ranged from 1.4 to 24.4 days, with an overall mean of 6.6 days. On average, the number of days with total ice cover decreased by 11.3 days between the two periods, with statistically significant changes at 11 stations. After 2020, river ice phenomena occurred only sporadically, mainly as frazil ice and border ice along the middle and lower Vistula. Complete ice cover formed only in 2021 and 2026, lasting from several days to approximately two weeks.

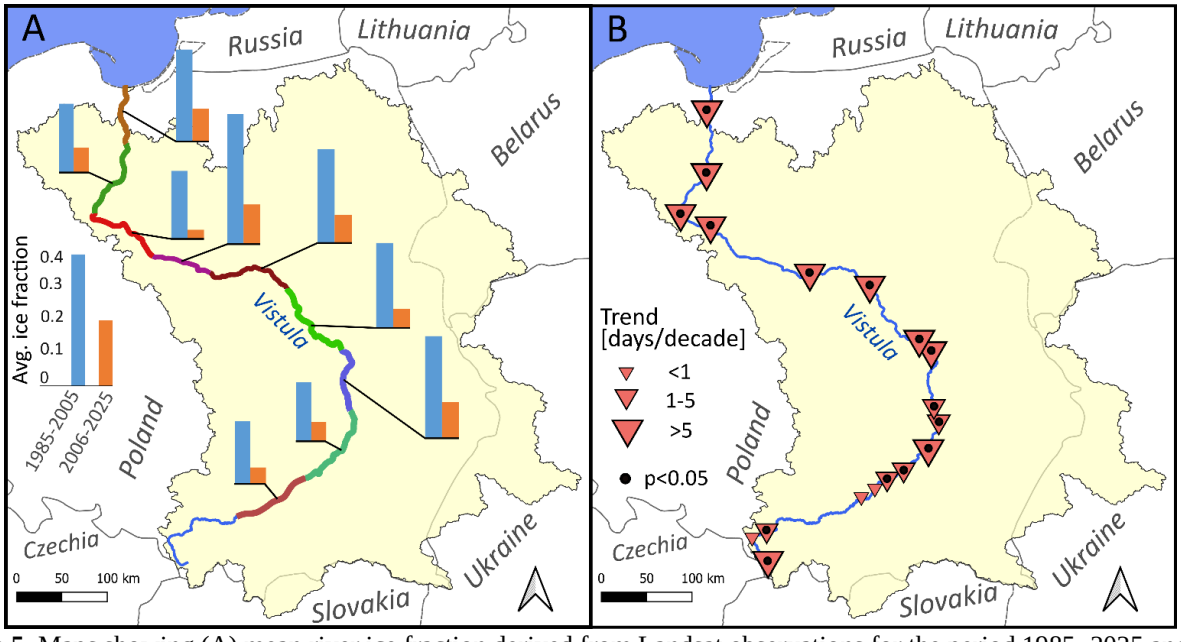


Figure 5. Maps showing (A) mean river ice fraction derived from Landsat observations for the period 1985–2025 and (B) the magnitude of the decreasing trend in the number of days with river ice phenomena during the period 1950–2020.

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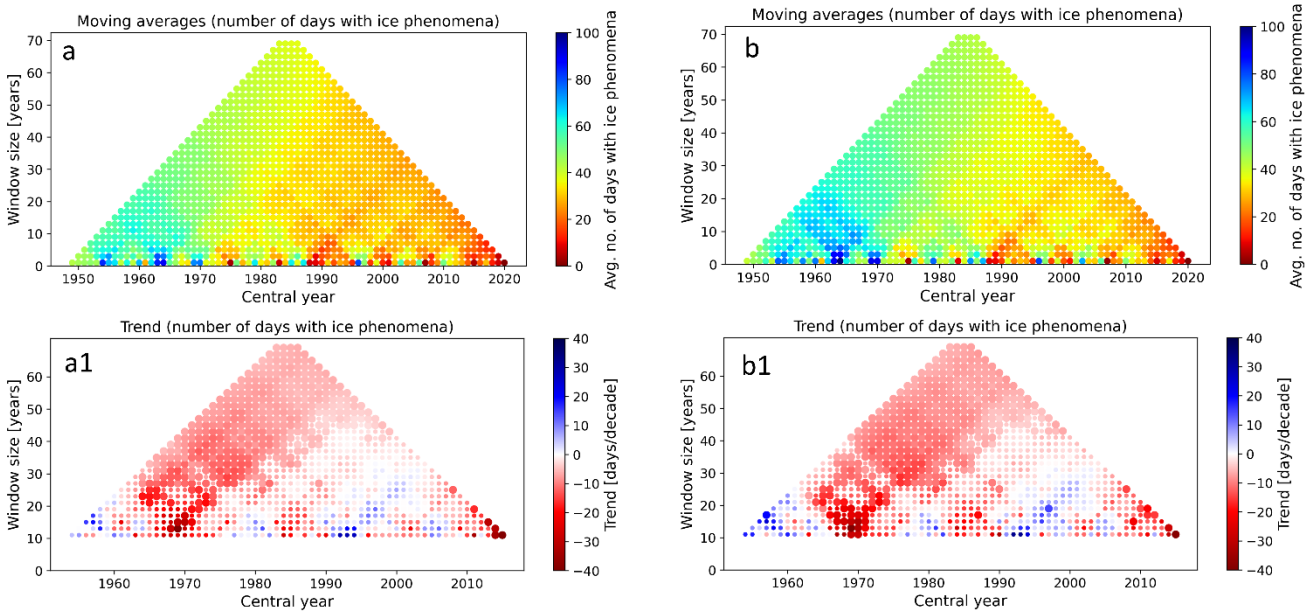


Figure 6. MARTA diagrams showing moving averages and trends in the number of days with river ice phenomena during 1950–2020 for (a, a1) all stations with complete measurement series and (b, b1) stations not directly affected by anthropogenic pressures.

Temporally, the greatest river ice extent occurred in January (based on Landsat data from 1985–2025), when ice covered 40% of the river's surface area. Slightly lower ice coverages were observed in December (16%) and February (23%). The minimum ice extents occurred in November (3%) and March (4%). During 1985–2025, a decrease in the proportion of ice-covered area along the Vistula River was observed. Depending on the river section, the reduction between the two sub-periods (2006–2025 and 1985–2005) ranged from 12.5 to 26.4 percentage points, with an average decrease of 17.7 percentage points. Notably, the strong agreement between the spatial distribution of river ice extent and the results obtained from in situ observations confirms high consistency between these two data sources.

Table 1. Trends (1950-2020) and the number of days with ice phenomena and ice cover at measuring stations.

Station Code	Trend in the number of days with ice phenomena [days/decade]	Avg. number of days with ice phenomena		Difference in ice phenomena between 1986–2020 and 1950–1985 (percentage change)	Avg. number of days with total ice cover		Difference in total ice cover between 1986–2020 and 1950–1985 (percentage change)
		1950-1985	1986-2020		1950-1985	1986-2020	
S1	**-7.2**	52.8	21.5	**-31.3 (-59.3%)**	20.8	6.2	**-14.6 (-70.2%)**

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S3	-1.3	37.5	27.0	**-10.6 (-28.3%)**	11.4	1.8	**-9.5 (-84.2%)**
S4	**-2.6**	22.8	11.6	**-11.3 (-49.1%)**	10.1	2.5	**-7.7 (-75.25%)**
S13	-0.4	12.5	8.4	-4.1 (-32.8%)	3.8	1.4	-2.5 (-63.2%)
S14	0.0	11.0	7.8	-3.2 (-29.1%)	4.7	1.9	-2.8 (-59.6%
S15	**-2.7**	22.8	16.3	-6.5 (-28.5%)	6.3	4.2	-2.1 (-33.3%)
S17	**-3.0**	28.5	23.2	-5.3 (-18.6%)	12.2	5.8	**-6.4 (-52.5%)**
S22	**-7.2**	46.9	18.1	**-28.8 (-61.4%)**	26.9	4.1	**-22.8 (-84.8%)**
S24	**-4.9**	49.2	32.0	**-17.2 (-35%)**	23.8	7.6	**-16.2 (-68.1%)**
S25	**-8.2**	60.5	29.8	**-30.9 (-50.7%)**	28.5	10.7	**-17.8 (-62.5%)**
S28	**-10.0**	67.6	32.1	**-35.5 (-52.5%)**	37.8	15.5	**-22.2 (-59.0%)**
S29	**-7.7**	69.7	40.5	**-29.2 (-41.9%)**	31.4	13.7	**-17.7 (-56.4%)**
S33	**-7.8**	63.6	28.9	**-34.6 (-54.6%)**	10.0	3.5	-6.5 (-65.0%)
S36	**-7.1**	73.5	44.5	**-29.1 (-39.5%)**	34.3	24.4	-9.9 (-28.9%)
S42	**-8.3**	67.6	38.2	**-29.5 (-43.5%)**	15.8	5.0	**-10.8 (-38.3%)**
S44	**-9.1**	69.7	33.7	**-36.0 (-51.6%)**	13.2	2.2	**-11.0 (-83.3%)**
S46	**-8.4**	66.0	35.9	**-30.0 (-45.6%)**	13.0	3.7	**-9.3 (-71.5%)**
S51	**-10.5**	66.9	27.9	**-39.0 (-58.3%)**	9.3	5.9	**-3.4 (-36.6%)**
Mean	**-6.2**	49.4	26.5	**-22.8 (-46.4%)**	17.4	6.7	**-10.7 (-61.5%)**

Statistically significant values at the $p < 0.05$ level are shown in **bold**. The significance of trends was assessed using the Mann–Kendall test, while differences between the two sub-periods were evaluated using the Mann–Whitney U test.

Assuming an average Vistula River water surface area of 257.8 km², the mean ice-covered area decreased from approximately 64.5 km² during 1985–2005 to approximately 20.6 km² during 2006–2025. Note that these values are approximate, as they were derived by multiplying the mean percentage of ice cover detected in Landsat imagery by the average water surface area of the Vistula River. Since the river surface area varies over time depending on hydrological conditions, the actual ice-covered area during individual winters may differ from these estimates.

Overall, the results indicate that the Vistula River's ice regime is shaped by the interplay between climate change and local anthropogenic factors. At the whole-river scale, a clear long-term decline in river ice phenomena is observed, primarily driven by increasing air and water temperatures. Climatic variability provides the general environmental background controlling the overall characteristics of the Vistula ice regime, while spatial variability in river ice occurrence is strongly influenced by anthropogenic activities, reflecting the local effects of reservoirs, thermal and chemical pollution, and river channel regulation. River sections characterized by the least anthropogenic modification exhibited the highest frequency of river ice phenomena and the strongest relationship with thermal conditions, whereas these relationships were considerably weaker in heavily

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modified sections. These results demonstrate that the response of the Vistula River's ice regime to contemporary climate warming is spatially heterogeneous and substantially modified by human activity.

5. Discussion

The above results indicate that the temporal and spatial variability of river ice phenomena along the Vistula River results from the interplay between climate change and local anthropogenic transformations. While climate change dictates the overall direction of ice regime transformation, human activities locally modify the river's response, leading to pronounced spatial differentiation of river ice processes. Thus, the contemporary ice regime of the Vistula River reflects the superposition of processes operating across multiple spatial scales, from basin-wide climatic drivers to local anthropogenic impacts.

The observed changes along the Vistula River's longitudinal profile are consistent with findings from numerous studies of rivers across the Northern Hemisphere, which have demonstrated later ice formation, earlier ice break-up, shorter duration of river ice phenomena, and reductions in ice thickness and volume over time (Beltaos and Prowse, 2009; Newton and Mullan, 2021; Vuglinsky, 2017; Imrit et al., 2022; Fukś, 2023; Szczerbińska and Siwek, 2025). In some regions, a gradual disappearance of the total river ice cycle has also been observed (Fukś and Wiejaczka, 2025b). The results presented here indicate that during the analyzed period, the Vistula River has transformed from a river characterized by a complete seasonal ice cycle into a river where ice phenomena now occur only episodically.

The increase in air temperature from 1950 to 2020, together with the accelerated warming trend since the mid-1980s, has been widely observed across Europe (Dong et al., 2017; Twardosz et al., 2021). Recent studies attribute this transition to the combined effects of several processes, including increased radiative forcing from rising greenhouse gas concentrations, a rapid decrease in sulfate aerosol emissions leading to increased solar radiation reaching the Earth's surface, and changes in atmospheric circulation over the North Atlantic and Europe (Wild, 2009; Nabat et al., 2014; Masson-Delmotte et al., 2021; Marsz and Styszyńska, 2022). The strong relationship between air temperature and the frequency and duration of river ice phenomena indicates that atmospheric thermal conditions represent the primary factor controlling long-term variability in the Vistula River's ice regime. This suggests that the observed reduction in river ice occurrence should be interpreted primarily as the river system's response to ongoing climate warming.

This study demonstrated that anthropogenic pressure represents the second key factor shaping the Vistula River's contemporary ice regime. The results indicate that anthropogenic modifications of the river ice regime occur primarily through three mechanisms: (i) alterations in the water's physicochemical properties, (ii) changes in the thermal regime, and (iii) modifications of hydraulic flow conditions.

Changes in the river water's physicochemical properties are associated with the discharge of mine, industrial, and municipal waters, resulting in water temperature increases and mineralization. This process was most pronounced in the upper Vistula River, where the development of mining activities in the Upper Silesian Coal Basin since the 19th century has led to extensive mine drainage and the discharge of highly mineralized and heated waters into the Przemsza and Gostynia rivers, as well as

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directly into the Vistula River (Bednorz, 2012; Janson, 2024). During the second half of the 20th century, the contribution of mine waters to the total Vistula discharge downstream of these tributaries periodically reached several to several dozen percent, with mineralization exceeding 3000–5000 mg·L^{-1} (Gajowiec and Różkowski, 1988; Maksymiak-Lach et al., 2006; Kasprzak et al., 2016). Some Vistula tributaries exhibited mineralization exceeding 30,000 mg·L^{-1}. The discharged waters were characterized by particularly high concentrations of Cl^- and SO_4^{2-} ions, which lower the freezing point of water (Pawłowski, 2017). Additionally, the elevated temperature of mine waters, typically 10–20 °C, further limits the potential for river ice formation (Marszelewski and Pius, 2021; Barzantny et al., 2025). A similar mechanism, although operating on a much smaller spatial scale, has also been observed downstream of large industrial facilities, power plants, and urban agglomerations, including the areas of Kraków and Warsaw, where the discharge of wastewater and heated water contributed to a reduction in total ice cover occurrence.

The second mechanism of anthropogenic influence was reservoir operations, which affect both the thermal and hydraulic regimes of rivers. The Goczałkowice Reservoir limits the transport of mobile ice forms and releases warmer water during winter, leading to a decreased frequency of river ice phenomena downstream of the dam, similarly to observations from other reservoirs (Soja and Wiejaczka, 2014; Jasek and Pryse-Phillips, 2015; Fukś et al., 2024; Fukś and Wiejaczka, 2025b). A similar pattern is observed for the Włocławek Reservoir. Upstream of the dam, the reduced flow velocity and transition from typical riverine conditions to a more lacustrine environment promote the accumulation of mobile ice forms and the development of consolidated ice cover, while increasing this section's susceptibility to ice jam formation (Grześ, 1991; Kolerski, 2015; Pawłowski and Kolerski, 2022). In contrast, downstream of the dam, a marked decrease in river ice occurrence is observed for approximately 90 km along the river's course (Pawłowski, 2009; Majewski, 2011; Gorączko, 2013; Pawłowski, 2017). These results indicate that reservoirs do not solely contribute to the disappearance of river ice phenomena but may also locally enhance their development through modifications to hydraulic conditions.

The obtained results also demonstrate that anthropogenic pressure has a spatially varying effect that depends on the dominant type of impact. The strongest modifications of the ice regime occurred in the upper Vistula River, which is affected by both increased water temperature and high mineralization. In the river's middle course, local thermal pollution sources associated with industrial and municipal activities dominated, whereas in the lower course, the operation of the Włocławek Reservoir and activities related to navigation maintenance, including icebreaking operations and industrial activity, were the most important. Consequently, anthropogenic pressure does not produce a uniform river system response but instead promotes diverse transformations of the ice regime, which vary depending on the type and intensity of local environmental modifications.

The gradual decline of ice phenomena in the Vistula River may have long-term consequences for both the abiotic and biotic components of the river environment. Reduced ice occurrence alters flow hydraulics, affecting sediment transport, erosion, and deposition (Cheng et al., 2025). The disappearance of ice jams and mobile ice forms is particularly significant, as these phenomena strongly influence the spatial variability of morphogenetic processes and bank erosion. Consequently, a decrease in the frequency of river ice phenomena may reduce the importance of cryogenic processes in river channel evolution. Changes in the ice regime may also modify habitat conditions and the functioning of river ecosystems (Thellmann et al., 2021). The

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presence of ice cover regulates light, thermal, and hydrodynamic conditions, which in turn influence biogeochemical processes and the functioning of microorganism and fish communities (Cruaud et al., 2020; Thellmann et al., 2021). Therefore, a shorter ice-covered period may lead to changes in the structure of biological communities and deterioration of overwintering conditions for aquatic organisms.

Future research should focus on quantitatively assessing the relative influence of different factors on river ice regime transformations. This includes a numerical assessment of the relative contributions of overall climate warming and local anthropogenic factors, such as changes in the physicochemical properties of water, river channel regulation, reservoir operation, or the discharge of heated waters. Separating the effects of these factors is essential for reliably predicting future changes in river ice regimes. An equally important research direction is assessing the consequences of declining ice phenomena for river system functioning, including morphogenetic processes, habitat conditions, ecosystem functioning, and biogeochemical processes. A key issue is determining whether the observed disappearance of river ice leads to persistent changes in river ecosystem functions. Given the projected continuation of climate warming, this knowledge will be crucial for improving our understanding of river systems and for planning actions related to river conservation and water resource management.

6. Limatations

The hydrological data used in this study originate from more than seven decades of hydrological observations conducted across multiple research programs, carried out by various institutions at numerous hydrological stations. Although considerable effort was devoted to verifying the continuity of observations, digitizing historical yearbooks, and identifying missing records, time series from some stations remained incomplete, and the quality of the available data was often difficult to assess. To minimize this limitation, the long-term temporal analyses were restricted to stations with near-complete observation records, whereas the spatial analyses included all available stations. Accordingly, the study's spatial coverage was maximized without compromising the reliability of long-term trend assessments.

Landsat observations are inherently limited by revisit frequency, cloud cover, and the imagery's spatial resolution. Consequently, short-lived and mobile ice phenomena may remain undetected, particularly under rapidly changing weather conditions. To minimize this limitation, the analysis focused on long-term mean values derived from multiple Landsat observations. The ice detection procedure applied to satellite imagery was based on an algorithm developed and comprehensively validated for the Vistula River (Fukś et al., 2026, in press).

The influence of anthropogenic factors was assessed primarily based on the spatial correspondence between observed ice occurrence patterns and human impacts documented in previous studies. Therefore, this study identifies plausible mechanisms explaining spatial variability rather than quantitatively assessing the individual contribution of each anthropogenic factor. Future research based on both hydrological modelling and detailed field investigations may provide more detailed numerical insights into each factor's relative importance.

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Although the Vistula River represents a valuable model of a large Central European river, the magnitude of individual anthropogenic pressures may vary between river systems. However, the general relationship between climate warming and local human impacts identified in this study is expected to be relevant for many temperate-zone rivers undergoing similar environmental changes.

Finally, although each dataset has inherent limitations, the integration of multiple independent data sources in this study substantially enhances the reliability of the identified relationships. The consistency between in situ observations, satellite-derived ice cover data, and climatic trends suggests that the main conclusions are robust, as they do not depend solely on constraints from a single observational approach.

7. Conclusions

This study investigated the temporal and spatial patterns of river ice occurrence along the Vistula River, one of Europe's longest rivers. Particular attention was given to identifying the factors controlling the observed changes, highlighting the highly complex processes that shape the river's ice regime. The study's main conclusions are as follows:

1) From 1950 to 2025, the Vistula River basin experienced a significant transformation of winter climatic conditions, including a systematic increase in air temperature, shorter periods of sub-zero temperatures, and fewer freezing days. These changes led to a substantial water temperature increase and a reduction in the number of days with water temperatures suitable for ice formation, demonstrating a clear transfer of climatic signals from the atmosphere to the river. The results confirm that contemporary climate warming is the primary driver of the observed changes in the Vistula River's ice regime.
2) Between 1950 and 2025, the Vistula River's ice regime changed significantly. In the mid-20th century, the river was characterized by a regularly occurring complete ice cycle; however, it now exhibits only sporadic and short-lived ice phenomena, which are entirely absent in some river sections. All analyzed cross-sections showed consistent changes, with shorter durations and reduced frequency and intensity of ice phenomena. The rate of these changes also varied significantly spatially, influenced by both regional environmental conditions and anthropogenic factors. On average, the number of days with river ice phenomena decreased by 6.2 days per decade. Furthermore, a river ice extent decrease of approximately 18 percentage points was observed in 2006–2025 compared with 1985–2005.
3) The occurrence of river ice phenomena along the Vistula River shows marked spatial variability. The upper Vistula River is the most significantly altered section in terms of its ice regime, where mining, industrial activities, and the operation of hydraulic infrastructure have driven significant ice cover decreases and, in some areas, its complete disappearance. In contrast, the middle Vistula River exhibits the lowest level of anthropogenic modification, as indicated by the highest number of days with river ice phenomena.
4) Human activities significantly influence river ice regimes. In most cases, anthropogenic factors such as mining and industrial activities, heated water discharge, river channel regulation, and hydraulic structures contribute to a reduced

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ice cover extent and shorter periods of ice occurrence. However, these effects are not always unidirectional: hydrotechnical modifications may locally promote longer ice persistence, particularly upstream of reservoirs. The results suggest that anthropogenic effects on river ice regimes may be greater than previously assumed and should be more extensively considered alongside climate change when assessing changing ice conditions.

Funding

This research was funded in whole or in part by the National Science Centre, Poland (grant no. 2025/57/N/ST10/00545). For the purpose of Open Access, the author has applied a CC-BY public copyright licence to any Author Accepted Manuscript (AAM) version arising from this submission.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors used ChatGPT to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as required and take full responsibility for the content of the published article.

Author contributions

Maksymilian Fukś: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Writing – original draft; **Łukasz Wiejaczka:** Writing – original draft; Writing – review & editing.

Data availability

All datasets used in this study are publicly available through scientific literature and open-access research data repositories. Landsat satellite data and ERA5 reanalysis data are available through the Google Earth Engine Data Catalog at: https://developers.google.com/earth-engine/datasets/catalog/landsat and https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_DAILY_AGGR (accessed: 7 July 2026). Contains modified Copernicus Climate Change Service Information (2026). Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus Information or Data contained in this publication. Hydrological data, including water temperature and river ice occurrence records for the period 1980–2024, are available from the online repository of the IMWM-NRI at: https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/ (accessed: 7 July 2026). Historical records of river ice occurrence on the Vistula River for the period 1949–1980 were obtained from the Hydrological Yearbooks of Surface Waters – Vistula (1949–1981), published by the Polish State Institute of Hydrology and Meteorology (until 1970) and subsequently by the Institute of Meteorology and Water Management (from 1971 onwards). These data were digitized manually for the purposes of this study. Data on the temporal and spatial variability of river ice phenomena, enabling reproduction of the results presented in this study, are available at: https://zenodo.org/records/21991427 (DOI:

https://doi.org/10.5194/egusphere-2026-6596
Preprint. Discussion started: 4 November 2026
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https://doi.org/10.5281/zenodo.21991427). The training dataset used for the random forest model is available at: https://zenodo.org/records/20083432 (DOI: https://doi.org/10.5281/zenodo.20083432).

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