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Long-Term Changes in the Thermal and Ice Regime of the Biebrza River (Northeastern Poland) in the Era of Global Warming

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Abstract: In the context of ongoing environmental changes, particularly against the backdrop of global warming, significant attention is being given to areas of exceptional natural value that, in many aspects, retain a pristine character. One such area is the Biebrza River in northeastern Poland, which, together with the wetlands in its basin, forms one of the most valuable ecosystems of its kind in Europe. This study analyses the changes in the thermal and ice regime for two hydrological stations, Sztabin and Burzyn, in the period from 1959 to 2023. It was found that the average annual water temperature in this period for the Biebrza River increased by 0.28 °C/decade, and in the case of ice phenomena, statistically significant changes for both stations showed a decline, with an acceleration of the ice cover disappearance by an average of 3 days/decade. These recorded changes should be considered unfavourable, as they will affect the transformation of both the biotic and abiotic characteristics of the river itself, as well as the natural elements associated with it.

Keywords: water temperature; ice phenomena; wetlands; climate changes

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1. Introduction

Water temperature in rivers and ice phenomena occurring in specific latitudes are fundamental characteristics of these ecosystems, determining their functioning. Numerous studies to date describe the influence of water temperature on processes that are closely dependent on thermal conditions [1–10].

Today, with global warming in mind, one of the key topics in potamology (the study of rivers) is the assessment of changes in thermal conditions and the occurrence of ice phenomena, as confirmed by numerous publications on the subject [11–14].

In the context of ongoing environmental transformations, which, in the case of human activity, can occur very quickly and drastically [15], it is particularly important to have knowledge about the scale of these changes in relation to areas that are valuable for their natural qualities. One such example is the Biebrza River (northeastern Poland), where the wetlands within its catchment are among the most valuable ecosystems of this type in Europe. A key element of this area is the Biebrza River itself, which, through seasonal water level changes (flooding), enables the functioning of other components of the hydrosphere. This area is protected in the form of a national park, the highest level of protection. It is also worth noting that, in some aspects, this river serves as a reference point for research conducted in other parts of Europe [16]. It is therefore natural that Biebrza and the conditions in its catchment have been the focus of many previous studies across various disciplines [17–22]. Against this backdrop, however, the thermal regime of the river and ice phenomena have not been commonly addressed. Here, one can refer to, among others, the analysis of water temperature (1961–1995) and ice phenomena (1961–2000) for rivers in the Biebrza Basin [23]. Additionally, Marszelewski and Pius [24], based on data from a single station (Burzyn), established that between 1961 and 2014, it increased by 0.20 °C per decade. Additionally, as earlier studies of the thermal and ice regime of rivers in Poland show [25–27], there has been a gradual warming and shortening of the ice season over the past few decades, with the rate of these changes depending on the location of the catchment and the characteristics of the river itself. As Leach et al. [28], emphasise the impact of climate and environmental change on the thermal regime of streams is of interest to practitioners and representatives of biology, ecology, hydrology, engineering, and watershed management. Therefore, conducting research in this area, particularly in locations where high-quality data are available, is well justified.

Currently, with several decades of water temperature monitoring and observations of ice phenomena, an analysis of the direction and rate of changes in the thermal and ice regime of the Biebrza River has been conducted, which constitutes the primary objective of this research.

2. Materials and Methods

2.1. Study Area

The Biebrza River is located in northeastern Poland (Figure 1) and, in the hydrographic system, serves as a tributary of the Narew River, which then flows into the Vistula River. The length of the Biebrza River is 162.8 km, its catchment area is 7057.4 km^2, and its gradient is 0.36 [‰] [29]. Due to its hydrological conditions, the river has a strongly developed nival regime, meaning that the average spring runoff exceeds 180% of the average annual runoff. Rivers of this type in Poland are characterised by the greatest variations in runoff throughout the annual cycle [30]. According to Poland's regional division, the area through which the Biebrza flows has been classified as an independent mesoregion: 843.32 Biebrza Basin [31]. During the last glaciation, this depression formed a glacial valley, where, after the retreat of intense water flows, peat formation processes occurred, resulting in a several-meter-thick layer of peat.

The Biebrza Valley is divided into three parts: the northern basin, the central basin, and the southern basin. In the northern part, the width of the valley is several kilometres, and the area of peatlands is approximately 20,000 hectares. The central part consists of a vast flat area with a width of 40 km, occupied by swamps covering about 40,000 hectares. In contrast, the last fragment of the Biebrza Valley has a meridional layout, where the western slopes of the valley are high and steep, while the eastern ones are flat. The extent of the Biebrza Marshes is one of the favourable features that facilitate their maintenance in a natural state [32]. The existing conditions in the Biebrza Basin are very beneficial from a natural perspective, as there is a high diversity of flora and fauna. In 1993, the Biebrza National Park was established (Figure 1), making it the largest national park in Poland. The most valuable feature of the park is the Biebrza River valley, which contains the largest complex of peatlands in Poland, where rare, threatened, and endangered species of plants and animals have been preserved. The Biebrza Marshes are one of the most important habitats for wetland birds in Poland and Central Europe. The national park has been included in the Ramsar Convention list [33]. The Biebrza Valley is designated as a Natura 2000 area (PLB 200006, PLH 200008). One of the threats to the local waters is eutrophication [34].

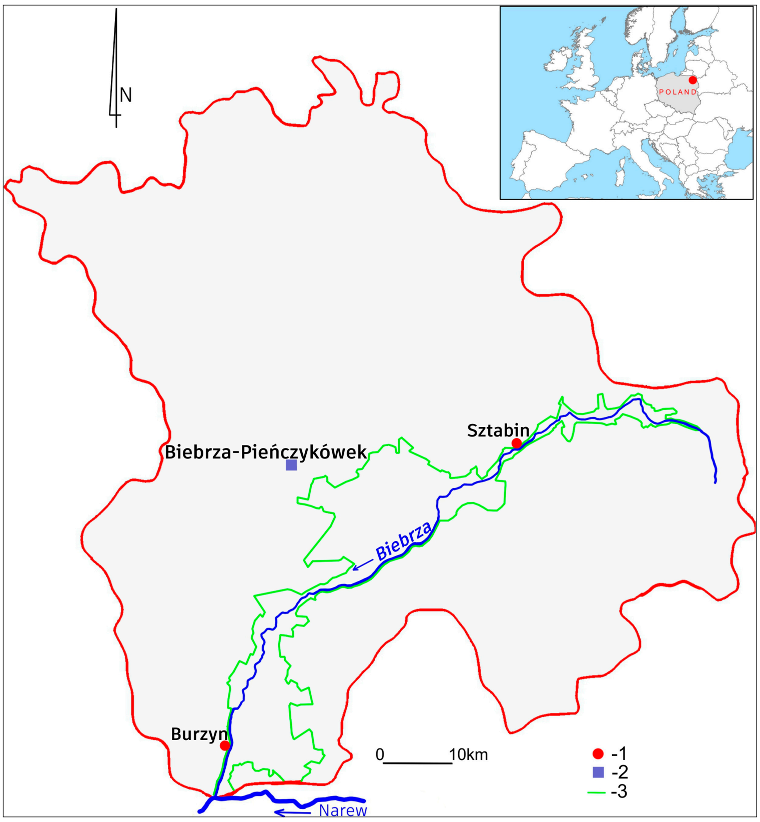

Figure 1. Location of the study area, 1—hydrological stations, 2—meteorological station, 3—boundary of the national park.

2.2. Materials

This study utilised data from the Institute of Meteorology and Water Management concerning daily water temperatures and ice phenomena for the Biebrza River (at the Sztabin and Burzyn stations) between 1959 and 2023. All analyses were conducted using Python version 3.11.9, chosen for its robust libraries and tools for data processing, statistical analysis, and visualization, which enabled a comprehensive examination of long-term changes in the river's thermal and ice regimes. Water temperature was measured at a depth of 0.4 m below the surface, always at the same point. Ice phenomena were recorded by observers, where the first occurrence of ice in any form during a winter season marked the start of ice events. Similarly, the end of the ice phenomena was determined by the last occurrence of ice in any form noted at the same station during the same winter season. Additionally, the study used air temperature data from the Institute of Meteorology and Water Management, monitored through their standard observation procedures.

2.3. Methods

This study employed various statistical methods to examine temperature trends and ice dynamics at the Sztabin and Burzyn stations. This encompasses linear regression for evaluating long-term trends, the Mann–Kendall test for trend detection, the Pearson correlation coefficient for assessing relationships between variables, and Pettitt's test for identifying potential change points in the time series.

2.3.1. Linear Regression

Linear regression was utilised to quantify trends in air and water temperatures, along with the initiation and termination dates of ice. It was utilised to evaluate long-term trends in water and air temperatures, along with the commencement and conclusion dates of ice formation. Linear regression delineates the association between a dependent variable Y and an independent variable X through the equation

$$Y = \alpha + \beta X + \epsilon \tag{1}$$

where Y is the dependent variable (e.g., air temperature, water temperature); X is the independent variable (year); α is the intercept, indicating the baseline value of Y when $X = 0$; the slope β indicates the rate of change over time: a positive slope reflects an increasing trend, while a negative slope indicates a decreasing trend; and ϵ denotes the error term, capturing the deviation of observed values from the predicted values due to unaccounted variability or random fluctuations. A p-value was calculated to test the significance of each trend, where a p-value less than 0.05 was considered statistically significant. This p-value was calculated using the standard t-test for the slope coefficient β, based on the t-distribution of the regression residuals. Specifically, the t-statistic is calculated as

$$t = \frac{\beta}{SE(\beta)} \tag{2}$$

where $SE(\beta)$ is the standard error of the slope. The resulting t-statistic is used to determine the p-value, assessing the probability of observing such a trend if the true slope were zero. This approach is widely used in climate and environmental studies to examine trends [35,36].

2.3.2. Mann–Kendall Test

The non-parametric Mann–Kendall test was used to confirm trends without assuming a specific data distribution. It was used to confirm trends in the time series data without assuming any particular distribution. This test calculates Kendall's Tau τ statistic, which represents the strength and direction of a monotonic trend over time. The Mann–Kendall test is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(X_j - X_i\right) \tag{3}$$

where X_i and X_j are data points at times i and j, respectively; n is the total number of observations; and $sgn\left(X_j - X_i\right)$ is the sign function, which takes values of −1, 0, or 1. A positive S indicates an upward trend, while a negative S indicates a downward trend. The Mann–Kendall test is particularly useful for climate data, where trends may not be linear [37].

2.3.3. Pearson Correlation

To assess the relationship between air temperature and ice start/end dates, we employed Pearson's correlation coefficient (r), which measures the strength of linear associations between two variables. The Pearson correlation coefficient r is calculated as

$$r = \frac{\sum (x - \overline{x})\left(Y - \overline{Y}\right)}{\sqrt{\sum(x - \overline{x})^2 \sum(y - \overline{y})^2}} \tag{4}$$

where X and Y are the paired values for two variables (e.g., air temperature and ice start date), and $\overline{x}$ and $\overline{y}$ are their means. The value of r ranges from −1 to 1, where 1 indicates a perfect positive linear relationship, −1 indicates a perfect negative linear relationship, and values close to 0 imply weak or no linear relationship. A p-value is calculated to determine the significance of the correlation, with a p-value less than 0.05 considered significant [38].

2.3.4. Pettitt's Test

Pettitt's test was applied to detect abrupt changes in the time series, identifying years where significant shifts in trends occurred. This test is based on the Mann–Whitney statistic and is particularly suited for non-normally distributed data with a single change-point. Pettitt's test statistic Ut is calculated as follows:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} sgn\left(X_j - X_i\right) \quad (5)$$

where X_i and X_j are observations before and after time t, n is the total number of observations, and $sgn\left(X_j - X_i\right)$ is the sign function. The test identifies the year t where the change-point (maximum absolute value of U_t) occurs. A p-value is computed to assess the significance of this change-point, with a p-value less than 0.05 indicating a statistically significant change. Pettitt's has been widely applied in climate studies to detect shifts in temperature and precipitation patterns [39].

3. Results

The trend analysis results for air temperature during specific seasonal periods, as shown in Table 1 and Figure 2, reveal significant warming trends across all three periods analysed, including the preconditioning period (September to November), ice season (December to February), and melting period (March to May). During the preconditioning period, which occurs before ice formation, the temperature trend shows a modest but statistically significant increase with a slope of 0.016 °C per year (p = 0.020). This upward trend suggests that autumn temperatures are gradually warming, which may delay the onset of ice formation on water bodies. As temperatures increase, the cooling period required for water to reach freezing levels extends, potentially impacting the timing of ice formation and the overall duration of ice cover. The ice season, representing the core winter months when ice cover is typically maintained, shows the highest warming trend among the three periods, with a slope of 0.047 °C per year, which is highly significant (p = 0.002). Rising temperatures during this period may reduce the stability and thickness of the ice, making it more vulnerable to mid-winter melting events. Such changes could lead to a decrease in the overall duration of ice cover, as thinner ice is more susceptible to breaking up earlier. The melting period, covering the early spring months, also reveals a statistically significant temperature increase with a slope of 0.024 °C per year (p = 0.002). This warming trend during the transition from winter to spring could accelerate ice breakup, leading to earlier melting.

The statistical analysis in Table 2 and Figures 3 and 4 showing air and water temperature relationships across seasonal periods at both Burzyn and Sztabin stations reveal significant insights into the seasonal dynamics. Table 2 presents the Pearson correlation and Kendall's Tau values for each season, highlighting the statistical significance and strength of these relationships. Additionally, Figures 3 and 4 provide evidence of these relationships, showcasing scatter plots with fitted linear regression lines for each season at both stations.

Table 1. Trend analysis results for air temperature during specific seasonal periods.

Period	Slope	Intercept	p-Value
Preconditioning	0.016	−26.38	0.020
Ice season	0.047	−97.09	0.002
Melting period	0.024	−41.83	0.002

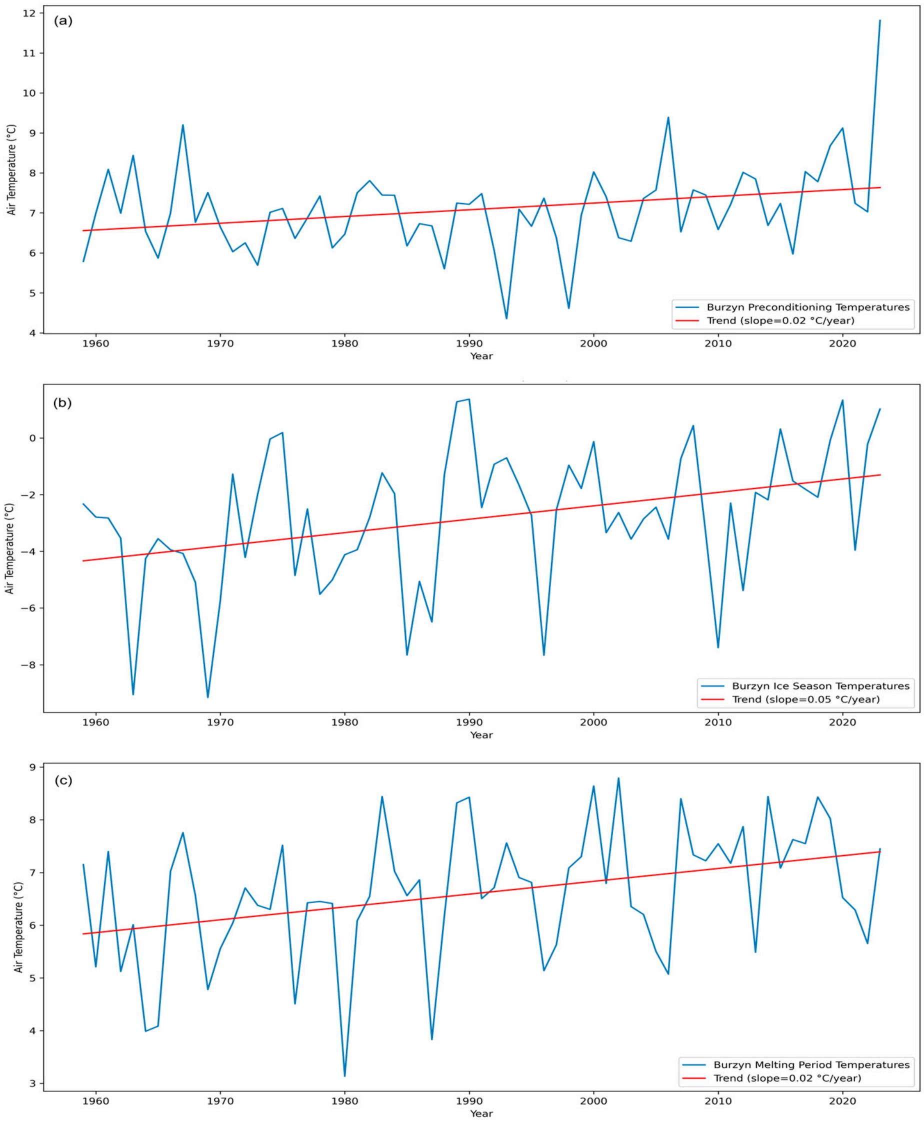

Figure 2. Seasonal air temperature trends for (**a**) preconditioning period (September to November), (**b**) ice season (December to February), and (**c**) melting period (March to May).

Table 2. Statistical test results for Kendall's Tau and Pearson correlation between air and water temperature during specific seasonal periods at Sztabin and Burzyn stations.

Statistical Test	Sztabin		Burzyn	
	Value	*p*-Value	Value	*p*-Value
Kendall's Tau—(preconditioning)	0.66	0.0000	0.66	0.0000
Kendall's Tau—(ice season)	0.43	0.0000	0.39	0.0000
Kendall's Tau—(melting period)	0.71	0.0000	0.70	0.0000
Pearson correlation—(preconditioning)	0.84	0.0000	0.84	0.0000
Pearson correlation—(ice season)	0.42	0.0000	0.43	0.0000
Pearson correlation—(melting period)	0.87	0.0000	0.86	0.0000

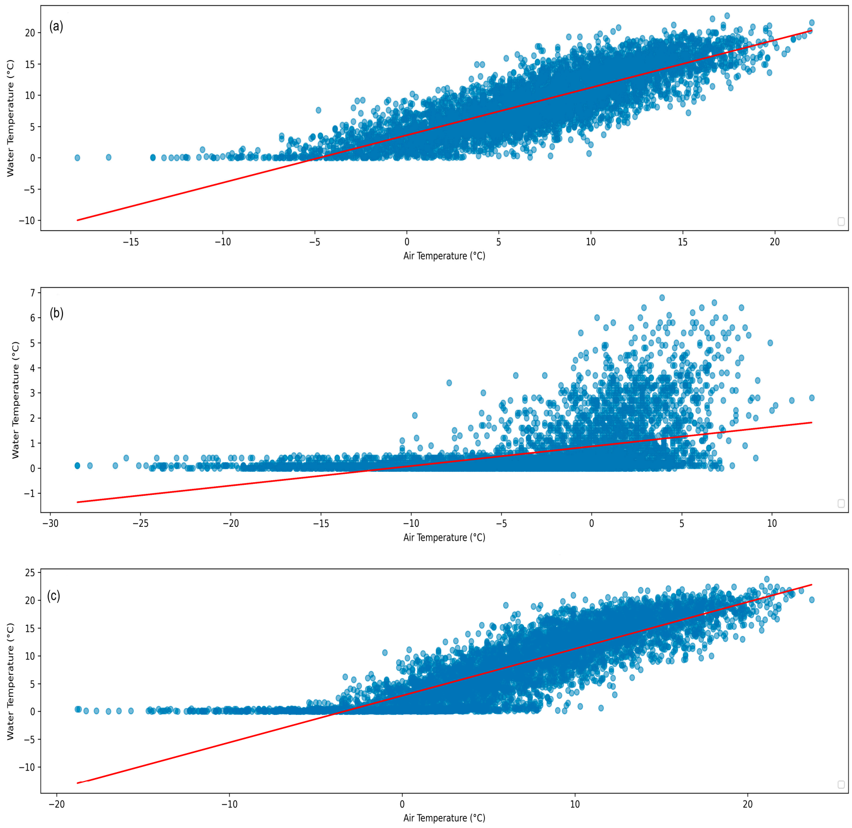

Figure 3. Seasonal relationship between air temperature and water temperature at Burzyn station during the (**a**) preconditioning period (September to November), (**b**) ice season (December to February), and (**c**) melting period (March to May).

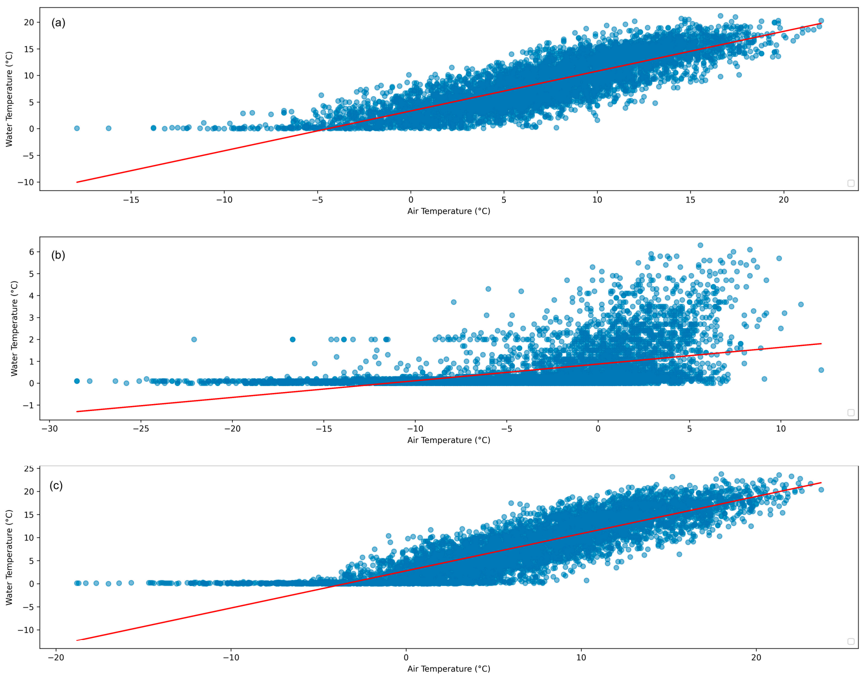

Figure 4. Seasonal relationship between air temperature and water temperature at Sztabin station during the (**a**) preconditioning period (September to November), (**b**) ice season (December to February), and (**c**) melting period (March to May).

During the preconditioning period (September to November), the relationship between air and water temperatures is strong and statistically significant, as indicated by high Kendall's Tau values (0.66 for both stations) and Pearson correlation coefficients (approximately 0.84 for both stations). This period, depicted in Figures 3 and 4, shows a tight clustering of data points along the regression line, suggesting that water temperature closely follows air temperature trends. The absence of ice cover during this period allows atmospheric temperatures to exert a more direct influence on water temperature.

In the ice season (December to February), the relationship weakens, as seen in the lower correlation values (Kendall's Tau of 0.43 for Sztabin and 0.39 for Burzyn; Pearson correlation around 0.42 for both). The weaker correlation during this season, illustrated in of Figures 3 and 4, is likely due to the presence of ice cover, which insulates the water and reduces direct thermal transfer between the atmosphere and the river water. The scatter plots for this season show a wider spread of data points, reflecting the reduced sensitivity of water temperature to fluctuations in air temperature.

The melting period (March to May) shows a resurgence in the strength of the air-water temperature relationship, with high Kendall's Tau values (0.71 for Sztabin and 0.70 for Burzyn) and Pearson correlation coefficients (around 0.87 and 0.86, respectively). Figures 3 and 4 highlights a close clustering of points along the regression line, similar to the preconditioning period. As ice cover diminishes, water temperatures respond more directly to atmospheric warming, resulting in stronger seasonal correlations.

Biebrza Pieńczykówek station exhibited a statistically significant increase in air temperature (0.029). The intercept values further corroborate the consistency of increasing temperatures, with *p*-values at 0.0000, affirming the significance of the trend. Table 3 presents the trend analysis results for water temperature, ice start, and ice end at the Sztabin and Burzyn stations. Both stations exhibited a statistically significant increase in water temperature (Figure 5).

Table 3. Trend analysis results for annual average water temperature, ice start, and ice end at Sztabin and Burzyn stations. The intercept represents the estimated value of the dependent variable (e.g., the day of ice end) at the hypothetical baseline of year 0, serving as a starting point for the linear trend.

Parameter	Sztabin			Burzyn		
	Slope	Intercept	*p*-Value	Slope	Intercept	*p*-Value
Water temperature	0.025	−40.87	0.0000	0.031	−54.36	0.0000
Ice start	0.084	−131.67	0.5816	0.260	−479.70	0.0251
Ice end	−0.38	880.41	0.0081	−0.382	893.80	0.0042

The continuous increase in water temperature indicates a general warming trend in air temperatures and implies a probable correlation between atmospheric and aquatic warming. The trends for ice start dates vary among stations (Figure 6). At Sztabin, the slope of 0.084 and a *p*-value of 0.5816 indicate the absence of a statistically significant trend, implying that the timing of ice formation has remained relatively stable. Conversely, Burzyn exhibits a positive slope of 0.260 with a *p*-value of 0.0251, signifying a significant postponement in ice start dates. This indicates that ice formation at Burzyn is occurring later in the year, probably due to rising temperatures.

As shown in Figure 5, the average annual water temperature in the Biebrza River remained relatively stable until approximately 1995, after which it began to exhibit a more pronounced upward trend. This suggests a potential shift in the thermal regime of the river that may be attributed to broader climatic changes or local environmental factors influencing water temperature. It is also evident that recent data points, particularly the last recorded value in 2023, have a substantial influence on the overall trend line, accentuating the positive slope. The change-point analysis indicates a significant shift around 1995, highlighting a period where warming accelerated. This suggests that the temperature increase is not uniform across the entire period but is rather concentrated in recent decades.

Both stations exhibited a negative trend in ice end dates (Figure 7), with slopes of −0.38 for Sztabin and −0.382 for Burzyn, accompanied by p-values of 0.0081 and 0.0042, respectively. The statistically significant trends demonstrate that ice is melting earlier in the year at both sites. The earlier ice melt further underscores the effect of increasing temperatures on seasonal ice dynamics, as the warming trend reduces the duration of ice cover on aquatic surfaces.

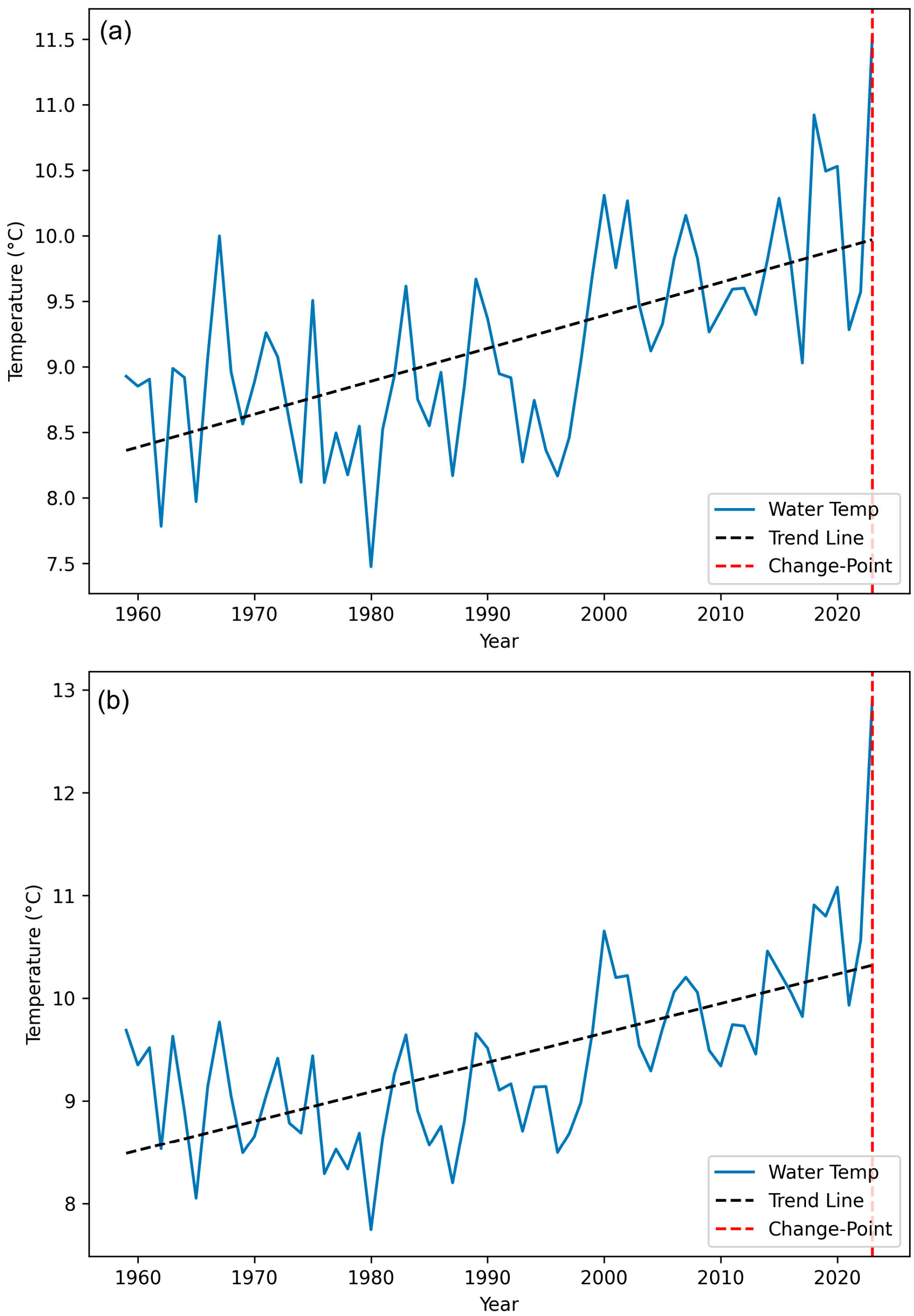

Figure 5. Course of average annual water temperature in the Biebrza River in the years 1959–2023: (**a**) Sztabin, (**b**) Burzyn.

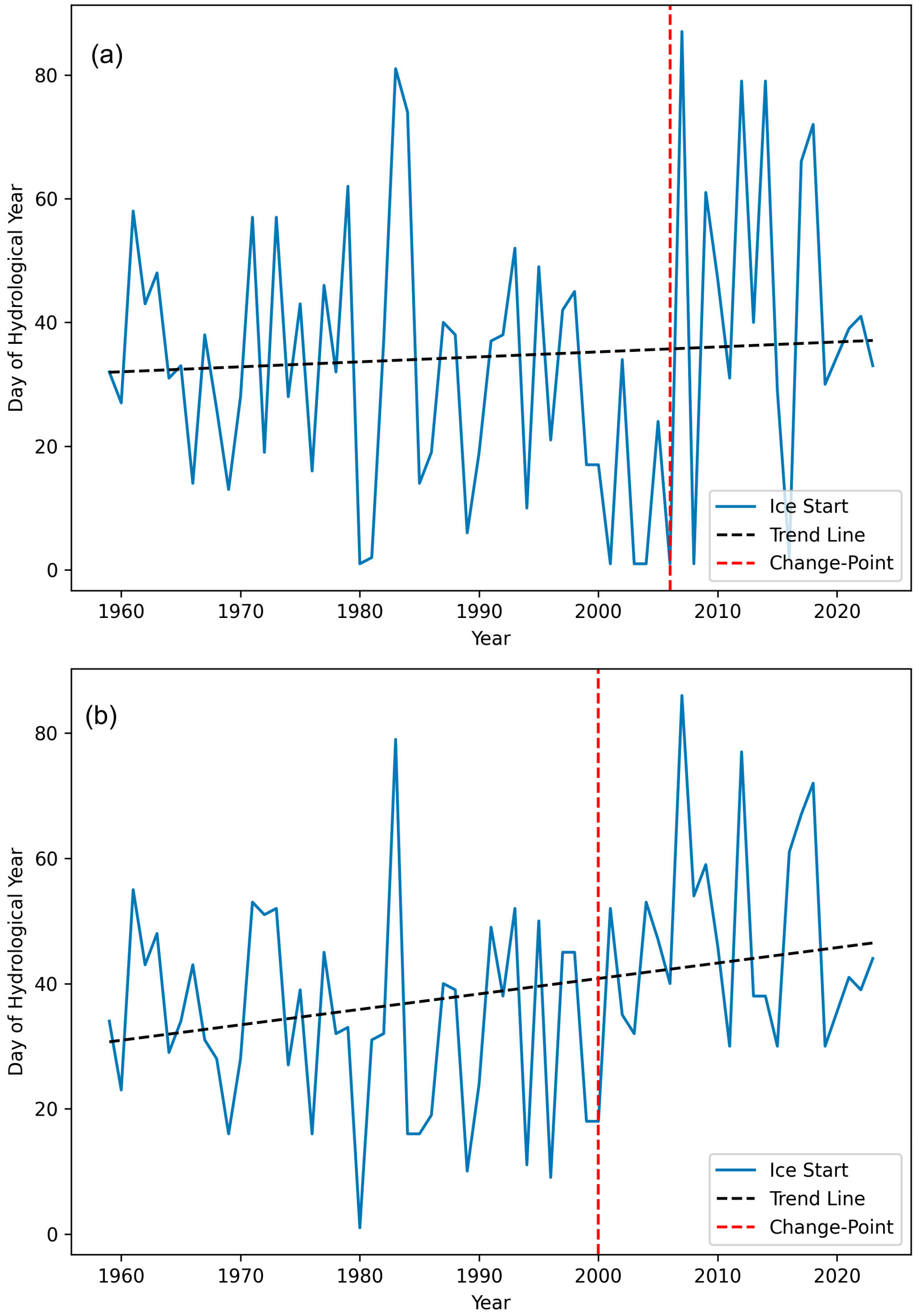

Figure 6. Variability of the start date of ice phenomena in the Biebrza River in the years 1959–2023: (**a**) Sztabin, (**b**) Burzyn.

Table 4 presents the results for Kendall's Tau, Pearson correlation, and Pettitt's test for the Sztabin and Burzyn stations, examining the correlations between temperature and ice phenomena variables. The Kendall's Tau analysis reveals a significant positive correlation between water temperature and air temperature at both stations, with Kendall's Tau values of 0.446 and 0.401 for Sztabin, and 0.451 and 0.401 for Burzyn, all exhibiting *p*-values of 0.0000. This statistically significant finding verifies a distinct increase in both air and water temperatures, indicating persistent warming in the area.

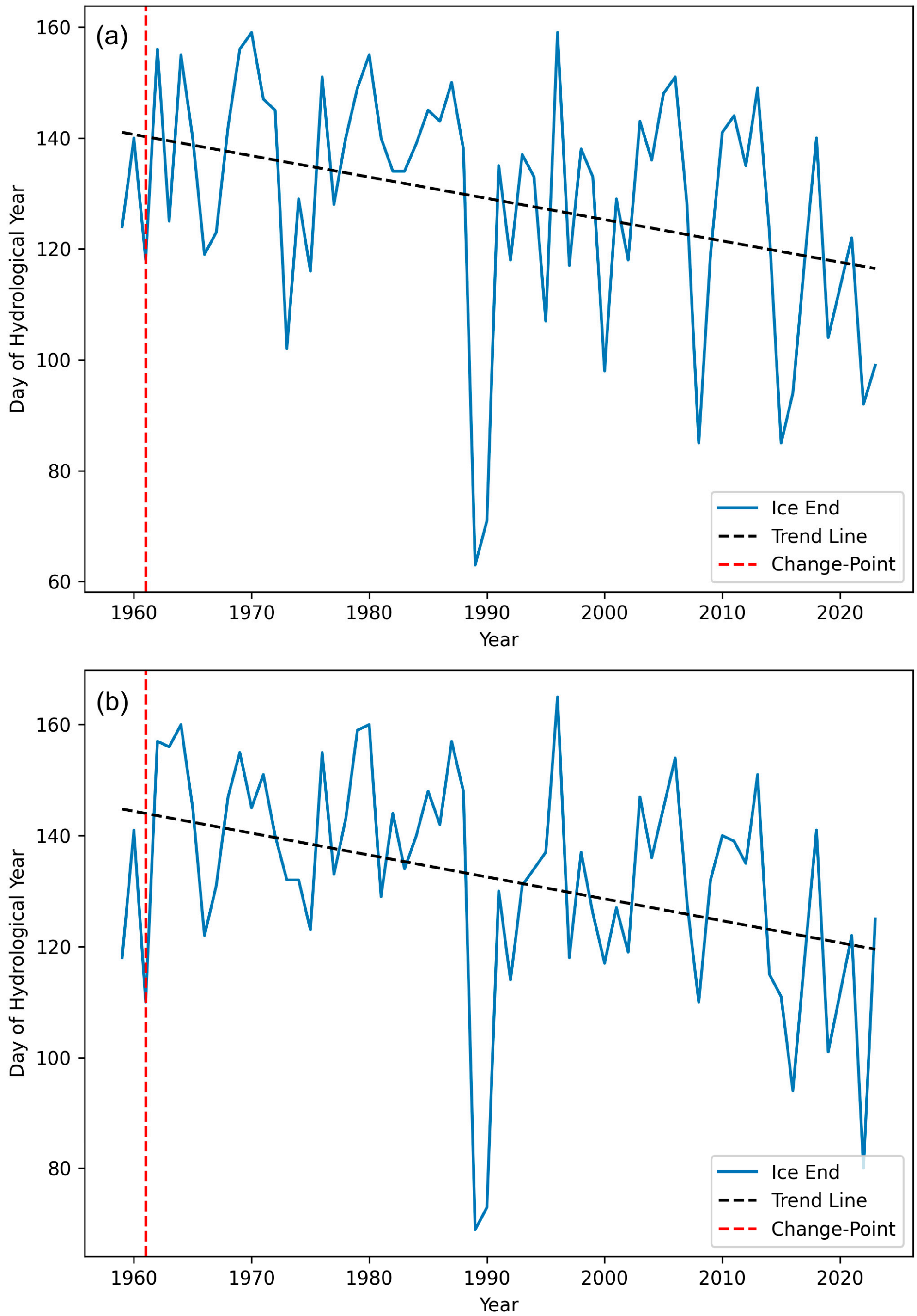

Figure 7. Variability of the end date of ice phenomena in the Biebrza River in the years 1959–2023: (**a**) Sztabin, (**b**) Burzyn.

The Pearson correlation analysis indicates a weak correlation between ice start and air temperature, with coefficients of 0.145 (p = 0.254) at Sztabin and 0.293 (p = 0.019) at Burzyn. The statistically significant finding at Burzyn indicates an acceleration in ice formation as temperatures rise, consistent with regional warming trends. The correlation between ice end dates and air temperature exhibits a robust negative relationship, with coefficients of −0.688 at Sztabin and −0.672 at Burzyn, both statistically significant with p-values of 0.0000. This inverse correlation indicates that elevated air temperatures correlate with earlier ice melting, thereby diminishing the duration of ice cover.

Table 4. Statistical test results for Kendall's Tau and Pearson correlation at Sztabin and Burzyn stations.

Statistical Test	Sztabin		Burzyn	
	Value	*p*-Value	Value	*p*-Value
Kendall's Tau—water temperature	0.446	0.0000	0.451	0.0000
Kendall's Tau—air temperature	0.401	0.0000	0.401	0.0000
Pearson correlation—ice start–air temp	0.145	0.254	0.293	0.019
Pearson correlation—ice end–air temp	−0.688	0.0000	−0.672	0.0000
Pettitt's test—water temperature	64	1.83	64	1.83
Pettitt's test—air temperature	64	1.83	64	1.83
Pettitt's test—ice start	47	0.659	41	0.044
Pettitt's test—ice end	2	1.96	2	1.82

Pettitt's test analysis was used to identify change points in water temperature, ice start, and ice end at the Sztabin and Burzyn stations from 1959 to 2023 (Figures 2–4). Both stations exhibited an upward trend in water temperature over the years, with statistically significant increases in each instance, reflecting the effects of regional warming. The Pettitt test detected change points in both water and air temperatures towards the conclusion of the series, coinciding with recent instances of rapid warming, likely influenced by overarching global climatic changes.

The analysis of ice duration trends and their relationship with seasonal air temperatures at Sztabin and Burzyn stations reveals significant insights. As illustrated in Figures 8 and 9, the trend analysis for ice duration indicates a decline in the length of ice cover over the years, which is statistically supported by both Pearson and Kendall's Tau tests. For Sztabin, the slope of the linear regression shows a notable decrease, suggesting a reduction in ice duration over time, with a statistically significant *p*-value ($p < 0.05$).

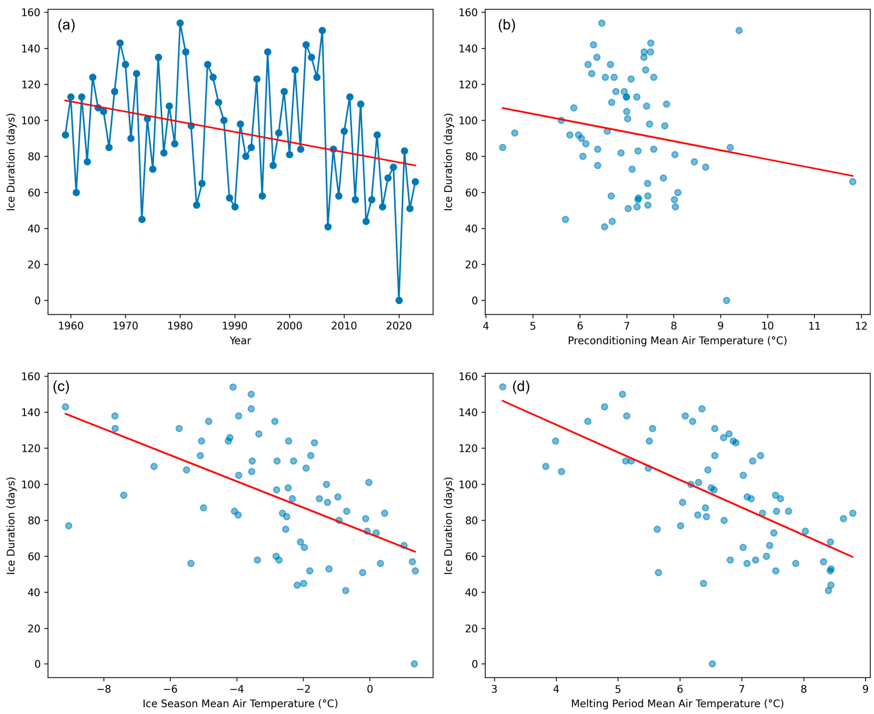

Figure 8. Seasonal analysis of (**a**) ice duration trend, (**b**) relationship between ice duration and mean air temperature during the preconditioning period (September to November), (**c**) relationship between ice duration and mean air temperature during the ice season (December to February), (**d**) relationship between ice duration and mean air temperature during the melting period (March to May) at Sztabin station.

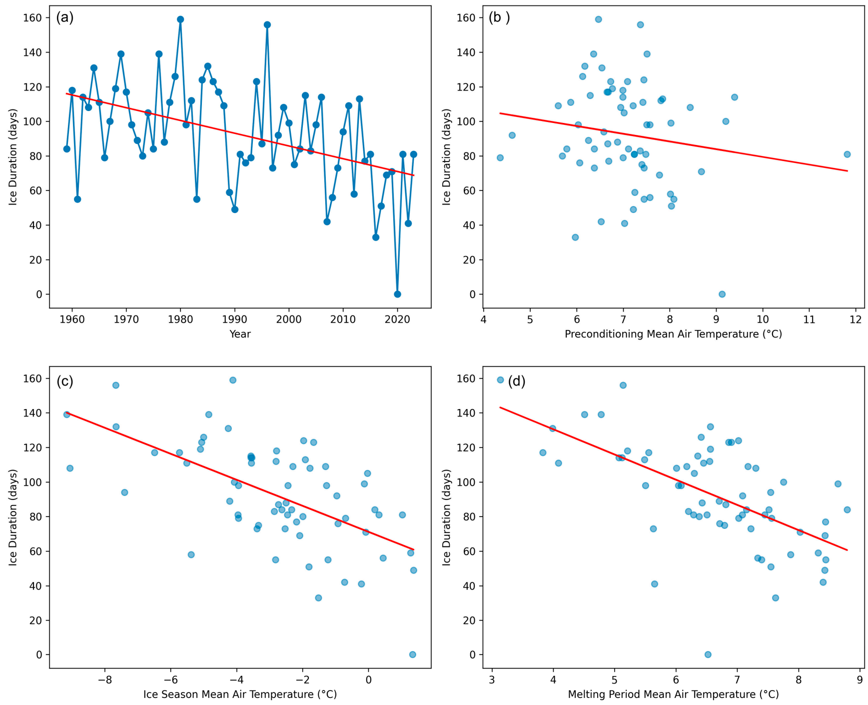

Figure 9. Seasonal analysis of (**a**) ice duration trend, (**b**) relationship between ice duration and mean air temperature during the preconditioning period (September to November), (**c**) relationship between ice duration and mean air temperature during the ice season (December to February), (**d**) relationship between ice duration and mean air temperature during the melting period (March to May) at Burzyn station.

The seasonal relationship between ice duration and air temperature during the preconditioning, ice season, and melting period reveals interesting patterns (Table 5). During the preconditioning period (September to November), the correlation between ice duration and air temperature is weak and not statistically significant at both stations, as shown by Pearson correlation coefficients of −0.17 for Sztabin and −0.16 for Burzyn, both with non-significant *p*-values ($p > 0.05$). This suggests that preconditioning air temperatures may have a limited effect on ice duration.

Table 5. Statistical test results for Kendall's Tau and Pearson correlation between ice duration and air temperature during specific seasonal periods at Sztabin and Burzyn stations.

Statistical Test	Sztabin		Burzyn	
	Value	*p*-Value	Value	*p*-Value
Kendall's Tau—(preconditioning)	−0.11	0.195	−0.13	0.128
Kendall's Tau—(ice season)	−0.41	0.0000	−0.42	0.0000
Kendall's Tau—(melting period)	−0.43	0.0000	−0.44	0.0000
Pearson correlation—(preconditioning)	−0.17	0.166	−0.16	0.190
Pearson correlation—(ice season)	−0.55	0.0000	−0.60	0.0000
Pearson correlation—(melting period)	−0.59	0.0000	−0.60	0.0000

However, during the ice season (December to February), a stronger negative correlation between air temperature and ice duration is observed, with Pearson correlation coefficients of −0.55 for Sztabin and −0.60 for Burzyn, both statistically significant ($p < 0.001$). This implies that higher air temperatures during the ice season are associated with shorter ice cover durations, highlighting the influence of warmer winters on reducing ice persistence. Kendall's Tau results also support this significant negative relationship, with values of −0.41 for Sztabin and −0.42 for Burzyn ($p < 0.001$).

Similarly, during the melting period (March to May), the relationship between air temperature and ice duration remains significantly negative. Pearson correlation coefficients of −0.59 for Sztabin and −0.60 for Burzyn, along with Kendall's Tau values of −0.43 and −0.44, respectively (both $p < 0.001$), indicate that warmer spring temperatures are strongly associated with reduced ice durations. This finding emphasises the impact of spring warming on accelerating ice break-up and shortening the ice season.

4. Discussion

Several decades of data on the thermal and ice conditions of the Biebrza River indicate significant changes in their regimes. The steady increase in water temperature and the progressively earlier end of ice phenomena align with numerous studies on the subject [40–45].

The obtained results related to water temperature and ice phenomena are similar to previous findings for rivers in Poland, across lowland, mountainous, and coastal areas. The water temperature of the Warta River at a station in central Poland (Sieradz) increased by 0.19 °C per decade from 1956 to 2014 [46]. An analysis of mountain rivers in the Carpathians showed significant, increasing trends in annual water temperature in all cases, ranging from 0.33 to 0.92 °C per decade [47]. Over half a century, the temperature of the lowland Prosna River rose by as much as 1.4 °C [48]. Ice phenomena on the Vistula River (near Bydgoszcz) from 1947 to 2012 occurred later, ended earlier, and lasted on average over a month shorter [49]. For the Łeba River, a very clear downward trend was observed in the number of days with ice, directly linked to an increase in average winter air temperatures [50]. Based on data from the periods 1903–1960 and 2001–2012, the duration of ice cover was found to have decreased from around 100 to an average of 60 days [51].

The key issue lies in the consequences of the observed changes, which have a multifaceted impact. Water temperature and the presence of ice play a critical role in the basic life processes of organisms inhabiting river ecosystems and their surroundings. As mentioned earlier, this area is an important ornithological site, not only in Poland but also on a European scale. However, only a few species of waterfowl winter in this region [52]. It should be noted that northeastern Poland experiences the longest duration of ice cover on inland waters in the country [53]. In the case of the Biebrza River, the average acceleration of ice breakup during the analysed period was over 20 days, which significantly alters water availability and, consequently, affects the behaviour of birds. The reproductive period of various fish species is also dependent on the water temperature. According to Wiśniewolski et al. [54], analysing the ichthyofauna of the Biebrza and its tributaries, the earliest to spawn (in March) are pike and asp. As water temperatures rise, other species such as ide, perch, roach, and zander follow. The spawning period concludes with species like crucian carp, rudd, tench, and catfish. The shortened ice cover duration and the monthly temperature increase (ranging from 0.1 to 0.46 °C per decade) could potentially lead to behavioural changes in these species, ultimately causing a transformation of the biocenosis (community of living organisms).

The preservation of certain ecological attributes is strongly dependent on water quality. Intensified agriculture, industrial activity, and traffic-related pollution are the main threats to aquatic ecosystems. In the context of pollution transport, the Biebrza River should be considered not just within its basin but also in relation to its larger catchment area. According to Skoczko's research [55], the primary pollutants in the Biebrza River system are area-based, including nitrogen, phosphorus, and plant protection products. These pollutants originate mainly from agricultural activities. As outlined by the 91/271/EEC directive, specific sections of the Biebrza (from Kropiwna to Horodnianka and from Ełk to its mouth) are vulnerable to eutrophication. This vulnerability is defined by the accelerated growth of higher forms of plant life and algae, which can lead to undesirable disruptions in the biological balance of aquatic environments and a deterioration of water quality [56]. Hydrobiological monitoring of two measurement points on the Biebrza River, specifically focusing on phytoplankton, classified the water as having second-class quality (good ecological status/potential) [57]. Studies on the Berounka River (Czech Republic) from

2002 to 2007 indicated a significant increase in chlorophyll-a concentrations related to water temperature [58]. In the Thames River, high phytoplankton biomass and growth rates were observed when both flow and temperature conditions (ranging from 9 °C to 19 °C) aligned with long periods of sunlight [59].

In the context of water quality and the research presented in the article, the role of oxygen is crucial, as its concentration determines the hydrobiological conditions in aquatic ecosystems [60]. Rising water temperatures over the years have significant implications for the water's self-purification capabilities. Studies on river basins such as the Tunga-Bhadra, Sabarmati, Musi, Ganga, and Narmada (India) have shown that for every 1 °C increase in water temperature, there is a 2.3% decrease in oxygen saturation levels [61].

5. Conclusions

The thermal and ice regimes of rivers are key characteristics that influence numerous processes and phenomena within these ecosystems. Despite various scientific studies on the Biebrza River, the subject of its thermal and ice regimes has not been a primary focus of broader research until now. Based on detailed data collected from two hydrological stations between 1959 and 2023, trends in these regimes were identified. It was found that the average annual water temperature of the Biebrza River increased by 1.7 °C over the entire analysed period. Additionally, the end of ice phenomena has shortened by an average of 3 days per decade. These results point to significant changes in the thermal and ice regime of the Biebrza River, which will have important consequences for the functioning of its ecosystem, particularly in relation to the behaviour of waterfowl and fish, as well as water quality.

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