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Research article

Characteristics of river heatwaves in the Vistula River basin, Europe

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A R T I C L E I N F O

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A B S T R A C T

Rivers worldwide are warming due to the impact of climate change and human interventions. This study investigated river heatwaves in the Vistula River Basin, one of the largest river systems in Europe using long-term observed daily river water temperatures from the past 30 years (1991–2020). The results showed that river heatwaves are increased in frequency and intensity in the Vistula River Basin. The total number of river heatwaves showed clear increasing trend with an average rate of 1.400 times/decade, the duration of river heatwaves increased at an average rate of 14.506 days/decade, and the cumulative intensity of river heatwaves increased at an average rate of 53.169 °C/decade. The Mann-Kendall (MK) test was also employed, showing statistically significant increasing trends in the total number, duration, and intensity of heatwaves for all rivers, including the main watercourse of the Vistula River and its tributaries, with few exceptions. Air temperature is the major controller of river heatwaves for each hydrological station, and with the increase of air temperatures, river heatwaves will increase in frequency and intensity. Another impacting factor is flow, and with the increase of flow, river heatwaves tend to decrease in number, duration and intensity. The results suggested that mitigation measures shall be taken to reduce the effect of climate change on river systems.

1. Introduction

Climate change is impacting rivers worldwide [1–4]. One of the most significant effects of climate change on rivers is the warming of river water temperatures, which has been reported in many studies [5–7]. In recent years, extreme climatic events like heatwaves, are becoming more frequent [8–11].

With the impact of climate change and these extreme climatic events, river heatwaves will occur. By definition, river heatwaves are

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identified to occur when daily river water temperatures, are above a local and seasonally varying 90th percentile threshold [12,13]. For example [12], examined river heatwaves throughout the United States from 1996 to 2021, and found that river heatwaves are increased in frequency. However, how river heatwaves, including total number, duration and intensity respond to warming climate have largely remain unknown. This knowledge is especially important as river heatwaves might impact overall health and integrity of aquatic ecosystems [1]. For example [4], showed that river water quality tends to deteriorate during heatwaves [14]; found that heatwaves alter ecosystem functioning in a stream mesocosm experiment. In this regard, understanding the total number, duration, and intensity of river heatwaves is of great significance, which can provide reference for conducting appropriate mitigation measures.

To fill the above gap, this study investigated river heatwaves, including total number, duration and intensity in the Vistula River Basin, one of the largest river systems in Europe. Long-term observed daily river water temperatures and flow of 18 rivers (24 hydrological stations) from January 1, 1991 to December 31, 2020 were used. Meteorological variables like daily air temperatures were obtained from the nearby 14 meteorological stations.

Moreover, the Mann-Kendall (MK) test was applied to assess the overall heatwaves trends. The MK test offers several advantages for analyzing trends in hydrological variables [15,16], particularly in the context of river and lake heatwaves. Firstly, it is a non-parametric test, making minimal assumptions about the underlying distribution of data, which is advantageous when dealing with hydrological variables that may not follow normal distributions. Secondly, the MK test is robust against outliers, making it suitable for detecting trends in datasets prone to extreme values, such as those associated with heatwaves. Additionally, its simplicity and ease of implementation make it accessible for researchers and practitioners alike. Moreover, it provides a measure of trend strength through the calculation of the Kendall tau coefficient, allowing for the quantification of the magnitude of observed trends. Overall, the MK test is a valuable tool for identifying and characterizing trends in hydrological variables like river and lake heatwaves, aiding in the understanding of climate change impacts on aquatic ecosystems.

Note that a recent study in Ref. [13] investigated river heatwaves in the Vistula River Basin considering the overall trend of the whole basin, and there lacks of detailed analysis of river heatwaves for each hydrological station and possible impacting factors. The results reported in this study can benefit river management in the Vistula River Basin and provide reference for the analysis of river heatwaves in other regions as well.

2. Materials and methods

2.1. Study area and data

The Vistula (Wisła in Polish) River Basin is one of the largest river systems in Europe, which ranks ninth in terms of area. The basin area has an international character and covers the territory of four countries, and the river itself (1022 km) is located in Poland (sources Barania Gora 1116 m asl), the mouth to the Baltic Sea-Gdańsk Bay). The river itself is exclusively on Polish territory, flowing through its entire area from south to north. The tributaries of the Vistula River in the middle (in Fig. 1 is the fragment from the San

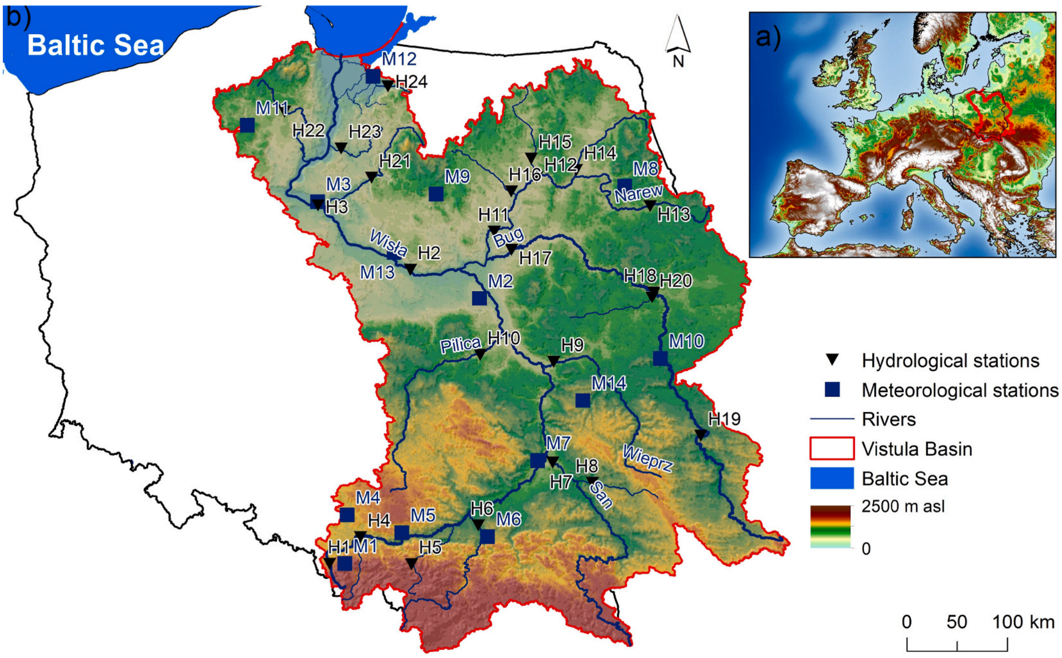

Fig. 1. Map showing the Vistula River Basin with detailed locations of the 24 hydrological stations (H1–H24) and the corresponding 14 meteorological stations (M1-M14).

River to the mouth of the Narew River) and lower reaches (in Fig. 1 from the Narew River to the Baltic Sea) are mainly characterized by a nivalve regime (from poorly formed to well formed), in the upper reaches it is a nivalve-pluvial and pluvial-nivalve, nivalve regime (with varying degrees of development) [17]. The average unit outflow for the entire Vistula River basin is 5.34 l-s-1-km-2 [18]. In terms of climatic conditions, the Vistula River Basin according to the Köppen-Geiger classification has been classified as type Dfb, i.e. cold without a dry season and with warm summers [19]. The land use structure is dominated by arable land and forests [20].

Table 1 provides the basic parameters of the analyzed rivers. In particular, various monitoring stations along the Vistula River and its tributaries were taken into account, covering a wide range of cases in terms of the extent and average altitude of the watersheds. Small rivers like the Wąska were considered, which, at the Pasłęk station, close to the Baltic Sea, drains an area of 246 km^2 with an average basin altitude of 6.7 m above sea level. Simultaneously, extensive watercourses like the Vistula River were also investigated, which, at the Toruń station, drains an area of 180390 km^2 with an average basin altitude of 32 m above sea level. However, along the Vistula River, other upstream stations were also considered. Among these, at the Skoczów station, the Vistula drains an area of 296 km^2 with an average basin altitude of 285.7 m above sea level. Additionally, the Raba River, a tributary of the Vistula, at the Stróża station, drains an area of 644 km^2 with an average basin altitude of 297 m above sea level.

Long-term observed daily river water temperatures and flow of 18 rivers (24 hydrological stations) from January 1, 1991 to December 31, 2020 were used in this study. Water temperature and flow are basic parameters monitored in detail in Poland by the Institute of Meteorology and Water Management-National Research Institute for several decades. Water temperature and flow measurements at all hydrological stations (H1–H24) are standardized and water temperature measurements are always conducted at the same location in the surface layer of water (at a depth of 0.4m). Air temperature measurements for the corresponding meteorological stations (M1-M14), on the other hand, represent readings from 2m above the ground surface from thermometers placed in meteorological shelter.

2.2. *Characteristics of river heatwaves*

A river heatwave is a period of unusually high river water temperatures and is defined by its duration and intensity. River heatwaves were identified to occur when daily river water temperatures were above a local and seasonally varying 90th percentile threshold, which was determined using daily river water temperature time series from 1991 to 2000 as baseline. The 90th percentile threshold has to be exceeded for at least five consecutive days to be considered as a river heatwave event, and two events with a break of less than three days are considered as a single event. In this regard, total number of river heatwaves (times), duration (consecutive period of time that water temperature exceeds the threshold, days), and cumulative intensity (sum of daily intensity anomalies for all consecutive periods of time that water temperature exceeds the threshold, °C) for each year can be computed. Initially, characteristics including the total number, duration and intensity were calculated for marine heatwaves using the R package 'heatwaveR' [21]. Since then, the method has been applied to calculate both lake and river heatwaves, such as lake heatwaves in Refs. [22,23], and river heatwaves in Refs. [12,13]. In this study, the same method was used to quantify river heatwaves in the Vistula River Basin. For each hydrological station, the observed daily river water temperatures were used for the calculation.

Table 1
Basic parameters of the analyzed rivers.

River	Station	Code	Location at river (km)	Basin area (km^2)	Altitude (m asl)	Corresponding meteorological station	Code
Wisła	Skoczów	H1	984.2	296	285.7	Bielsko-Biała	M1
Wisła	Kępa Polska	H2	331.9	168357	57.3	Płock	M13
Wisła	Toruń	H3	207.1	180390	32	Toruń	M3
Soła	Oświęcim	H4	3	1357	225.8	Katowice	M4
Raba	Stróża	H5	78	644	297	Kraków-Balice	M5
Dunajec	Żabno	H6	17.3	6739	172.4	Tarnów	M6
San	Radomyśl	H7	9.8	16838	138.8	Sandomierz	M7
Tanew	Harasiuki	H8	18.7	2035	164.5	Sandomierz	M7
Wieprz	Kośmin	H9	19.3	10293	115	Lublin-Radawiec	M14
Pilica	Białobrzegi	H10	45.9	8665	112	Warszawa	M2
Narew	Zambski Kościelne	H11	79.2	27807	79	Warszawa	M2
Narew	Nowogród	H12	179.2	20169	94	Białystok	M8
Narew	Narew	H13	406.2	1983	130.4	Białystok	M8
Biebrza	Burzyn	H14	7.9	6929	98.8	Białystok	M8
Pisa	Ptaki	H15	37.1	3576	104.9	Białystok	M8
Omulew	Białobrzeg Bliższy	H16	9.7	1788	94.4	Mława	M9
Bug	Wyszków	H17	17.5	38395	81.5	Warszawa	M2
Bug	Krzyczew	H18	244.5	25595	125.1	Włodawa	M10
Bug	Strzyżów	H19	530.8	8991	171.7	Włodawa	M10
Krzna	Malowa Góra	H20	8.4	3042	127.7	Włodawa	M10
Drwęca	Brodnica	H21	95.6	3540	67.4	Toruń	M3
Wda	Czarna Woda	H22	133.4	828	111	Chojnice	M11
Osa	Rogóźno 2	H23	19.1	1137	31.3	Toruń	M3
Wąska	Pasłęk	H24	13.6	246	6.7	Elbląg	M12

To assess the overall trend in total number, duration and intensity of heatwaves, the MK test [24,25] has been employed. The MK parameters primarily encompass Z, employed to detect statistically noteworthy trends at a predetermined confidence threshold of 95 % (p-value $\leq$0.05). This ensures a rigorous standard in identifying statistically significant trends in time series data. Additionally, Sen's slope β was employed to evaluate the linear trend gradient, with a positive β indicating an ascending trend and a negative value indicating a descending trend.

To analyze the possible factors, e.g., air temperature and flow, that may impact the total number, duration and intensity of river heatwaves, the coefficient of correlations between total number, duration and accumulative intensity of river heatwaves and air temperature and flow are calculated.

3. Results and discussion

3.1. *Total number of river heatwaves*

For each hydrological station, the total number of river heatwave events of each year was computed, and the trends based on the MK test were summarized in Table 2. Except H12 at River Narew and H23 at River Osa with the Sen's slope test does not provide a significance level, all the other 22 stations showed clear increasing trend for total number of river heatwaves ($p < 0.05$). Notably, the increasing rate varies between 0.814 times/decade (H10 at River Pilica) and 1.909 times/decade (H20 at River Krzna) with an average value of 1.400 times/decade.

The spatial pattern of the increasing rate of total number of river heatwaves for each hydrological station is shown in Fig. 2. As seen, the increasing rate of total number of river heatwaves is spatially heterogeneous, in some hydrological stations, e.g., H2 at River Wisła in the center, H8 at River Tanew in the south, and H20 at River Krzna in the east, the increasing rate of total number of river heatwaves are large, nearly two times of that in H10 at River Pilica, H16 at River Omulew, and H17 at River Bug.

The MK test applied on total number of heatwaves also showed statistically significant ($p \leq 0.05$) increasing trends for all rivers (see Table 3). In particular, Kośmin station on the Wieprz River (H9) showed the most pronounced positive trends (Z = 4.46, β = 0.17),

Table 2
Increasing rates of river heatwaves. '/' means insignificant trend (the Sen's slope test does not provide a significance level). The code corresponds to that list in Table 1. Colorbar ranges from green (lower values) to red (higher values).

Code	Increasing rate of total number (times/decade)	Increasing rate of duration (days/decade)	Increasing rate of cumulative intensity (°C/decade)	p-value
H1	1.439	15.388	58.55	$p \leq 0.05$
H2	1.753	20.196	70.988	$p \leq 0.05$
H3	1.177	17.264	55.742	$p \leq 0.05$
H4	1.355	13.081	45.725	$p \leq 0.05$
H5	1.037	15.137	67.794	$p \leq 0.05$
H6	1.602	13.956	51.169	$p \leq 0.05$
H7	1.448	12.667	53.621	$p \leq 0.05$
H8	1.771	13.686	46.438	$p \leq 0.05$
H9	1.562	15.996	65.09	$p \leq 0.05$
H10	0.814	7.442	32.055	$p \leq 0.05$
H11	1.359	12.534	47.375	$p \leq 0.05$
H12	/	/	/	p=0.07, 0.09, 0.10
H13	1.368	12.672	46.806	$p \leq 0.05$
H14	1.502	15.215	56.342	$p \leq 0.05$
H15	1.675	16.432	54.84	$p \leq 0.05$
H16	0.923	7.666	29.314	$p \leq 0.05$
H17	0.943	/	/	p=0.06, 0.07
H18	1.297	12.879	47.592	$p \leq 0.05$
H19	1.439	15.924	58.441	$p \leq 0.05$
H20	1.909	15.199	60.912	$p \leq 0.05$
H21	1.528	13.731	47.923	$p \leq 0.05$
H22	1.546	15.326	48.008	$p \leq 0.05$
H23	/	/	/	p=0.11, 0.33, 0.58
H24	1.359	22.229	71.834	$p \leq 0.05$

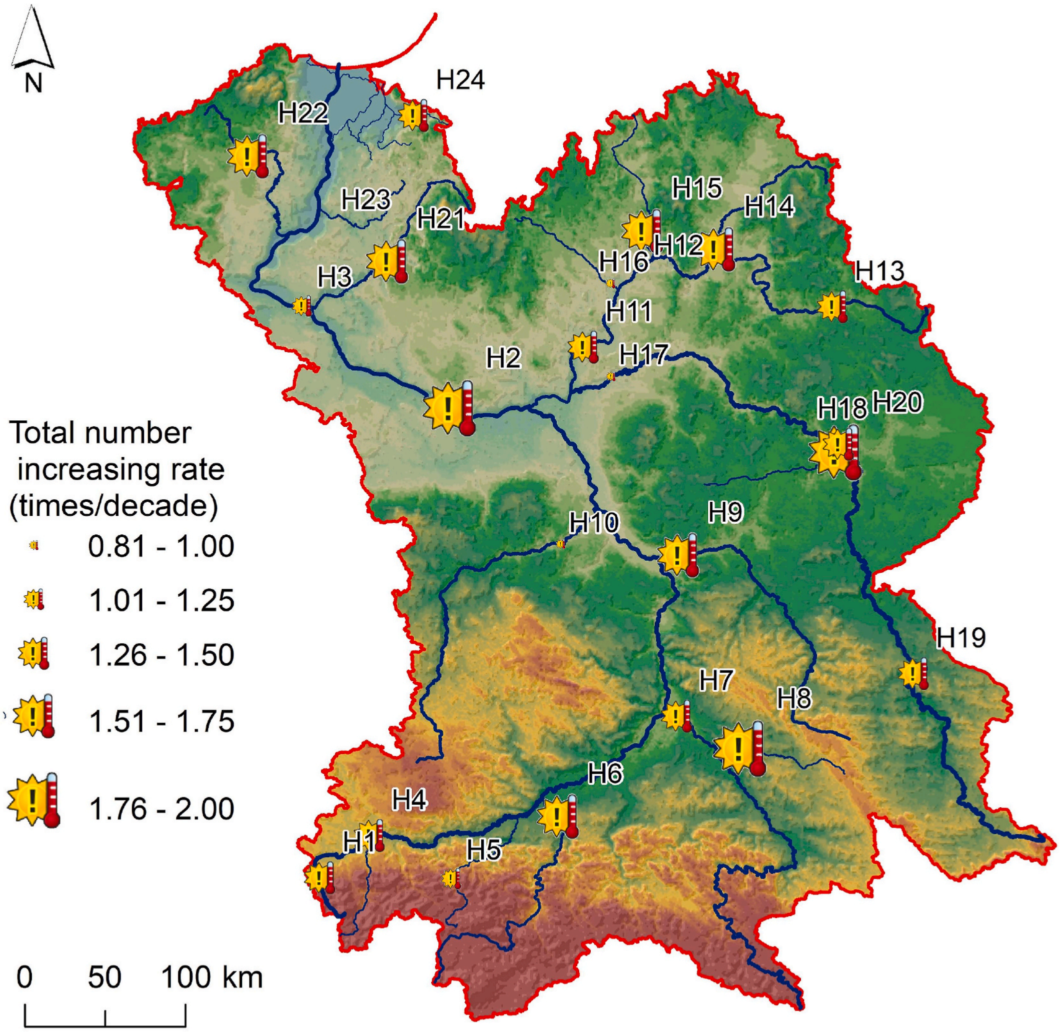

Fig. 2. Spatial pattern of the increasing rate of total number of river heatwaves for each hydrological station. The code corresponds to that lists in Table 1.

followed by other stations such as Strzyżów on the Bug River (H19, Z = 4.26), and Harasiuki on the Tanew River (H8, Z = 4.09). At the same time the, Nowogród station on the Narew River (H12) showed less marked, not statistically significant ($p = 0.07$), increasing trend. Moreover, the Rogóźno 2 station on the Osa River (H23), a tributary of the Vistula River close to the Baltic Sea, represents an exception, showing a negative trend, although not statistically significant ($p = 0.21$).

The negative trend in heatwave occurrence at the Rogóźno 2 station on the Osa River (H23), while not statistically significant, could be influenced by various factors such as local climate variability, land use changes, hydrological alterations and long-term climate trends. These factors may interact in complex ways, contributing to the observed decrease in heatwave frequency, although further analysis would be needed to determine the specific drivers behind this trend.

3.2. Duration of river heatwaves

For each hydrological station, the duration of river heatwave events of each year was computed, and the trends were summarized in Table 2. As shown, 21 out of the 24 stations (except H12 at River Narew, H17 at River Bug, and H23 at River Osa with the Sen's slope test does not provide a significance level) showed clear increasing trend for the duration of river heatwaves ($p < 0.05$). As seen, the increasing rate varies between 7.442 days/decade (H10 at River Pilica) and 22.229 days/decade (H24 at River Wąska) with an average value of 14.506 days/decade.

The spatial pattern of the increasing rate of the duration of river heatwaves for each hydrological station is shown in Fig. 3. As seen, the increasing rate of the duration of river heatwaves is spatially heterogeneous, in some hydrological stations, e.g., H2 at River Wisła in the center, and H24 at River Wąska in the north, the increasing rate of the duration of river heatwaves are large, nearly three times of that in H10 and H16.

Table 3
MK test parameters for testing significant trends of total number in river heatwaves. Colorbar ranges from red (negative values) to blue (positive values).

Code	River	Station	Total number of heatwaves		
			Z	β	p-value
H1	Wisła	Skoczów	3.37	0.14	$p \leq 0.05$
H2	Wisła	Kępa Polska	3.58	0.15	$p \leq 0.05$
H3	Wisła	Toruń	3.64	0.11	$p \leq 0.05$
H4	Soła	Oświęcim	2.90	0.11	$p \leq 0.05$
H5	Raba	Stróża	2.14	0.06	$p \leq 0.05$
H6	Dunajec	Żabno	3.06	0.13	$p \leq 0.05$
H7	San	Radomyśl	3.75	0.14	$p \leq 0.05$
H8	Tanew	Harasiuki	4.09	0.17	$p \leq 0.05$
H9	Wieprz	Kośmin	4.46	0.17	$p \leq 0.05$
H10	Pilica	Białobrzegi	2.58	0.06	$p \leq 0.05$
H11	Narew	Zambski Kościelne	3.64	0.13	$p \leq 0.05$
H12	Narew	Nowogród	1.79	0.06	0.07
H13	Narew	Narew	3.90	0.14	$p \leq 0.05$
H14	Biebrza	Burzyn	2.74	0.11	$p \leq 0.05$
H15	Pisa	Ptaki	3.51	0.15	$p \leq 0.05$
H16	Omulew	Białobrzeg Bliższy	2.49	0.08	$p \leq 0.05$
H17	Bug	Wyszków	2.78	0.10	$p \leq 0.05$
H18	Bug	Krzyczew	3.91	0.13	$p \leq 0.05$
H19	Bug	Strzyżów	4.26	0.13	$p \leq 0.05$
H20	Krzna	Malowa Góra	3.87	0.17	$p \leq 0.05$
H21	Drwęca	Brodnica	3.71	0.13	$p \leq 0.05$
H22	Wda	Czarna Woda	3.92	0.13	$p \leq 0.05$
H23	Osa	Rogóźno 2	-1.25	0.00	0.21
H24	Wąska	Pasłęk	2.66	0.14	$p \leq 0.05$

The MK test applied on duration of the heatwaves showed statistically significant ($p \leq 0.05$) increasing trends for all rivers (see Table 4). As observed for the total number of heatwaves, stations like Strzyżów (H19, Z = 4.36) and Krzyczew (H18, Z = 4.00) on the Bug River or Harasiuki on the Tanew River (H8, Z = 3.65) showed some of the highest increasing trends. Exceptions were represented by Nowogród station (H12, Z = 1.72) on the Narew River and Rogóźno 2 station (H23, Z = 0.55) on the Osa River that showed both non statistically significant increasing trends.

3.3. *Cumulative intensity of river heatwaves*

For each hydrological station, the cumulative intensity of river heatwave events of each year was computed, and the trends were summarized in Table 2. As shown, 21 out of the 24 stations (except H12, H17, and H23 with the Sen's slope test does not provide a significance level) showed clear increasing trend for the cumulative intensity of river heatwaves ($p < 0.05$). As seen, the increasing rate varies between 29.314 °C/decade (H16) and 71.834 °C/decade (H24) with an average value of 53.169 °C/decade.

The spatial pattern of the increasing rate of cumulative intensity of river heatwaves for each hydrological station is shown in Fig. 4. As seen, the increasing rate of the cumulative intensity of river heatwaves is spatially heterogeneous, in some hydrological stations, e.g., H2 in the center, H5 in the south, and H24 in the north, the increasing rate of the cumulative intensity of river heatwaves are large, two to three times of that in H10 and H16.

The MK test applied on cumulative intensity aligns with the outcomes observed for both total number of heatwaves and duration, showing statistically significant ($p \leq 0.05$) increasing trends for all rivers (see Table 5), with the only exceptions represented by Nowogród station (H12, Z = 1.80) on the Narew River and Rogóźno 2 station (H23, Z = 0.32) on the Osa River that showed both non statistically significant increasing trends. In addition, also in this case both Strzyżów (H19, Z = 4.14) and Krzyczew (H18, Z = 4.05) on the Bug River showed the highest increasing trends.

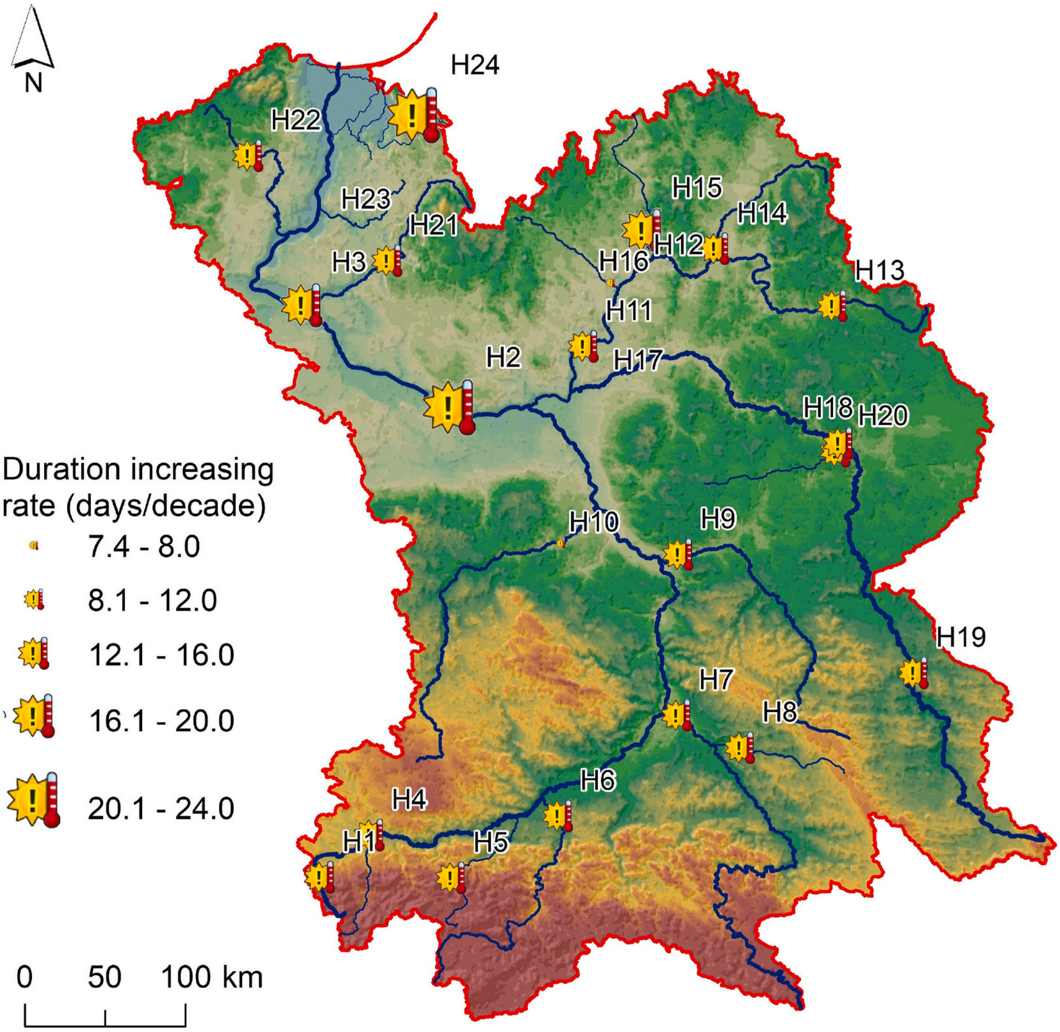

Fig. 3. Spatial pattern of the increasing rate of duration of river heatwaves for each hydrological station. The code corresponds to that lists in Table 1.

3.4. *Impacting factors on river heatwaves*

Analyzing the possible factors impacting the total number, duration and intensity of river heatwaves, it is found that air temperature is the main factor controlling river heatwaves, which can be seen from the coefficient of correlation (r) between total number, duration and accumulative intensity of river heatwaves and air temperatures (for 22 hydrological stations, $p < 0.05$). With the increase of air temperatures, river heatwaves will increase in frequency and intensity. For total number of river heatwaves, r varies from 0.347 to 0.733 with an average value of 0.615 for 22 stations; for duration of river heatwaves, r varies between 0.421 and 0.767 with an average value of 0.636 for 22 stations; for accumulative intensity of river heatwaves, r varies from 0.436 to 0.756 with an average value of 0.624 for 22 stations. Previous studies showed that air temperature is the major controller of river water temperatures [26–30]. With the impact of climate change, rivers are warming worldwide [5,6,31], and river water temperatures in the Vistula River investigated in this study are rising as well [32]. In this regard, there will be increased frequency of heatwaves in rivers, as is also shown in Ref. [12].

Flow might be the other factor impacting river heatwaves, which can be seen from the coefficient of correlation (r) between total number, duration and accumulative intensity of river heatwaves and flow (for 8 hydrological stations, $p < 0.05$). For total number of river heatwaves, r varies from −0.312 to −0.589 with an average value of −0.389 for 8 stations; for duration of river heatwaves, r varies between −0.273 and −0.444 with an average value of −0.360 for 8 stations; for accumulative intensity of river heatwaves, r varies from −0.299 to −0.410 with an average value of −0.345 for 8 stations. With the increase of flow, number, duration and intensity of river heatwaves tend to decrease, which is understandable as previous studies showed that flow can result in a damped response of river water temperatures to changes in air temperatures when river flow is higher [33,34].

Table 4
MK test parameters for testing significant trends of duration in river heatwaves. Colorbar ranges from red (negative values) to blue (positive values).

Code	River	Station	Duration (days)		
			Z	β	p-value
H1	Wisła	Skoczów	3.19	1.23	$p \leq 0.05$
H2	Wisła	Kępa Polska	3.45	1.91	$p \leq 0.05$
H3	Wisła	Toruń	3.38	1.38	$p \leq 0.05$
H4	Soła	Oświęcim	2.87	0.77	$p \leq 0.05$
H5	Raba	Stróża	2.88	0.86	$p \leq 0.05$
H6	Dunajec	Żabno	2.80	0.83	$p \leq 0.05$
H7	San	Radomyśl	3.37	1.22	$p \leq 0.05$
H8	Tanew	Harasiuki	3.65	1.23	$p \leq 0.05$
H9	Wieprz	Kośmin	2.43	0.50	$p \leq 0.05$
H10	Pilica	Białobrzegi	2.43	0.50	$p \leq 0.05$
H11	Narew	Zambski Kościelne	3.24	1.08	$p \leq 0.05$
H12	Narew	Nowogród	1.72	0.65	0.09
H13	Narew	Narew	3.36	1.11	$p \leq 0.05$
H14	Biebrza	Burzyn	2.52	0.78	$p \leq 0.05$
H15	Pisa	Ptaki	3.19	1.46	$p \leq 0.05$
H16	Omulew	Białobrzeg Bliższy	2.45	0.69	$p \leq 0.05$
H17	Bug	Wyszków	2.40	0.88	$p \leq 0.05$
H18	Bug	Krzyczew	4.00	1.33	$p \leq 0.05$
H19	Bug	Strzyżów	4.36	1.38	$p \leq 0.05$
H20	Krzna	Malowa Góra	3.71	1.25	$p \leq 0.05$
H21	Drwęca	Brodnica	3.34	1.13	$p \leq 0.05$
H22	Wda	Czarna Woda	3.66	1.22	$p \leq 0.05$
H23	Osa	Rogóźno 2	0.55	0.36	0.58
H24	Wąska	Pasłęk	3.18	1.70	$p \leq 0.05$

3.5. Potential impacts of river warming and heatwaves on aquatic system

This study found that river heatwaves increased in frequency and intensity for the Vistula River basin, which is consistent with [12], showing that river heatwaves are increased in frequency throughout the United States from 1996 to 2021. Warming of water temperatures and increasing in frequency, duration and intensity of river heatwaves will inevitably impact freshwater ecosystems in the study region as water temperature is one of the most important indicators that can control many physical and biogeochemical processes and the survival of aquatic species like fishes [6,35,36]. As summarized in Ref. [6], warming of river water can induce direct and indirect impacts on aquatic species, and aggravate pervasive issues like eutrophication, water pollution, and the spread of disease. Moreover, warming of river water can cause deoxygenation in water column, as shown in Ref. [35]. Considering heatwaves, studies in Refs. [4,14] showed that increased heatwaves will deteriorate river water quality and alter ecosystem functioning. Noteworthy is the quality and especially eutrophication, for which diffuse sources of pollution identified mainly with agriculture but also industrial and urban agglomeration wastewater are key. In the catchment area of the Baltic Sea, the Vistula is one of the largest sources of nutrients and other pollutants [37]. Over the past few decades, much has been done to improve this state of affairs, spending huge amounts of money to modernize and build sewer networks and wastewater treatment plants. For example, between 2003 and 2022 it was $23 billion [38]. As the results show, water temperature and therefore an elementary characteristic for water quality is subject to adverse changes. These changes are extreme in nature through an increase in the number and duration of heatwaves and, consequently, make it more difficult or more necessary to revise methods of rehabilitation of river ecosystems.

4. Conclusions

This study investigated river heatwaves in the Vistula River Basin, one of the largest river systems in Europe. The results lead to the following conclusions.

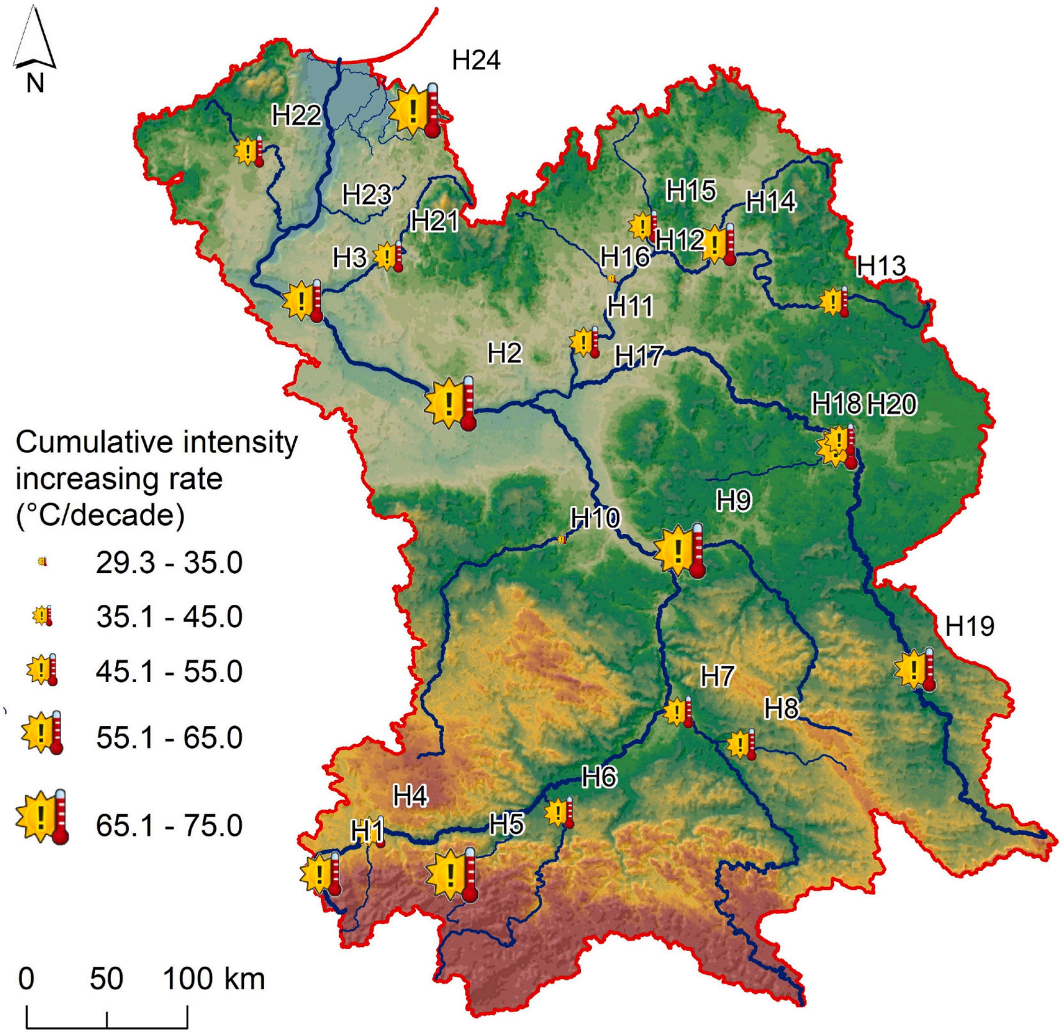

Fig. 4. Spatial pattern of the increasing rate of cumulative intensity of river heatwaves for each hydrological station. The code corresponds to that lists in Table 1.
Note that for some hydrological stations, e.g., H2 and H24, the increasing rates of number, duration and intensity of heatwaves are always large, while, for some hydrological stations, e.g., H10 and H16, the increasing rates of number, duration and intensity of heatwaves are always small. This might be induced by local climate and land use and land cover.

(1) River heatwaves are increased in total number, duration and intensity in the Vistula River Basin. Specifically, the total number of river heatwaves increased at an average rate of 1.400 times/decade, the duration of river heatwaves increased at an average rate of 14.506 days/decade, and the cumulative intensity of river heatwaves increased at an average rate of 53.169 °C/decade.
(2) The MK test showed increasing trends in total number, duration and intensity for all rivers, with statistically significant and more markedly positive trends for the main watercourse of the Vistula River and also for some tributaries, such as the Bug River. Two exceptions, represented by the Nowogród station on the Narew River and the Rogóźno 2 station on the Osa River, showed trends that were not statistically significant, with $p > 0.05$ and MK parameters close to 0. These exceptions may be affected by a range of factors including local variations in climate, including air temperature, shifts in land use patterns, alterations to hydrological systems and long-term climate trends.
(3) Air temperature is the major controller of river heatwaves, and with the increase of air temperatures, river heatwaves will increase in frequency and intensity. Flow also impacts river heatwaves, and with the increase of flow, river heatwaves tend to decrease in number, duration and intensity.

Data availability statement

Data will be made available on request.

Table 5
MK test parameters for testing significant trends of cumulative intensity in river heatwaves. Colorbar ranges from red (negative values) to blue (positive values).

Code	River	Station	Cumulative intensity (°C)		
			Z	β	p-value
H1	Wisła	Skoczów	3.10	5.34	$p \leq 0.05$
H2	Wisła	Kępa Polska	3.32	6.64	$p \leq 0.05$
H3	Wisła	Toruń	3.50	4.37	$p \leq 0.05$
H4	Soła	Oświęcim	2.92	2.57	$p \leq 0.05$
H5	Raba	Stróża	3.08	3.53	$p \leq 0.05$
H6	Dunajec	Żabno	2.75	3.06	$p \leq 0.05$
H7	San	Radomyśl	3.51	5.22	$p \leq 0.05$
H8	Tanew	Harasiuki	3.61	4.25	$p \leq 0.05$
H9	Wieprz	Kośmin	3.93	4.97	$p \leq 0.05$
H10	Pilica	Białobrzegi	2.50	1.92	$p \leq 0.05$
H11	Narew	Zambski Kościelne	3.25	4.05	$p \leq 0.05$
H12	Narew	Nowogród	1.80	2.09	0.071
H13	Narew	Narew	3.57	3.53	$p \leq 0.05$
H14	Biebrza	Burzyn	2.75	3.08	$p \leq 0.05$
H15	Pisa	Ptaki	3.19	4.17	$p \leq 0.05$
H16	Omulew	Białobrzeg Bliższy	2.36	2.85	$p \leq 0.05$
H17	Bug	Wyszków	2.22	3.15	$p \leq 0.05$
H18	Bug	Krzyczew	4.05	4.78	$p \leq 0.05$
H19	Bug	Strzyżów	4.14	5.00	$p \leq 0.05$
H20	Krzna	Malowa Góra	3.86	5.02	$p \leq 0.05$
H21	Drwęca	Brodnica	3.37	3.94	$p \leq 0.05$
H22	Wda	Czarna Woda	3.54	3.63	$p \leq 0.05$
H23	Osa	Rogóźno 2	0.32	0.26	0.747
H24	Wąska	Pasłęk	3.21	4.91	$p \leq 0.05$

CRediT authorship contribution statement

Quan Zhou: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Fabio Di Nunno:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Jiang Sun:** Writing – review & editing, Formal analysis, Data curation. **Mariusz Sojka:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Mariusz Ptak:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Yun Qian:** Writing – review & editing, Writing – original draft. **Senlin Zhu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Francesco Granata:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:The corresponding author Senlin Zhu is the Associate Editor of Heliyon, Earth Science Section. All the other authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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