Long-term temperature fluctuations in rivers of the Fore-Sudetic region in Poland

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ABSTRACT The paper presents an analysis of water temperature fluctuations in four rivers: Nysa Łużycka, Bóbr, Bystrzyca, and Nysa Kłodzka, in south-west Poland (Fore-Sudetic region) in the period 1971–2014. The obtained results show an evident increase in water temperature ranging from 0.15 °C·dec^{-1} to 0.33 °C·dec^{-1}. Such changes were particularly determined by changes in air temperature. Water temperature increased in two analyzed stations: Zielona Góra and Wrocław by 0.37 and 0.35 °C·dec^{-1}, respectively. While the variability of the rate of warming of particular rivers in the analyzed region should be associated with local factors occurring in the catchments, the contribution of forest cover is of key importance. A change in water temperature constituting its primary parameter will cause further transformation of the discussed river ecosystems. Combined with poor water quality, rising water temperatures can become a factor inhibiting further economic development of the Fore-Sudetic region in Poland.

KEY WORDS rivers – temperature – climate change – Sudety Mountains

PTAK, M. (2018): Long-term temperature fluctuations in rivers of the Fore-Sudetic region in Poland. Geografie, 123, 3, 279–294.
Received August 2017, accepted August 2018.

1. Introduction

Performing unequivocal hierarchisation of elements of key importance for the functioning of the natural environment, or affecting human life, is a difficult task. Nonetheless, one of the primary components determining the aforementioned issues is the presence of water (Choiński, Ławniczak, Ptak 2016). Its sufficient amount or deficit cause the development of biotic and abiotic features characteristic of a given region. Moreover, in the situations mentioned above, water can constitute a barrier or a stimulator of economic development of a given region (Choiński, Ptak, Strzelczak 2014).

In Poland, one of regions abundant in water is the area of the Sudetes and Fore-Sudetic region. In hydrological terms, it covers of catchments of left-bank tributaries of the Oder River (Fig. 1). Throughout centuries, rivers located there were an element determining the location of cities, and development of the glass, paper, chemical, and other industries. They currently play an important role in the context of functioning of energy engineering, tourism, water-sewage management, etc.

Water temperature is a key abiotic variable modelling the chemical composition of both waters and organisms inhabiting rivers and streams (St-Hilaire et al. 2012). In spite of the unquestionable role of water temperature for the functioning of the entire river ecosystem in the case of rivers flowing out from the Sudetes and in the territory of Poland, the issue has not been a popular subject of scientific research. The existing studies in the scope largely have a character of a review (Atlas 1987). Due to the above, it is justified to undertake more detailed investigation of the issues related to river water temperature fluctuations, and to fill the gap in the scope for this area of Europe.

In modern times, climatic changes are one of the most serious problems faced by humanity. The issue is of global character. In the case of Central Europe, according to Orgin (2015) – describing the situation for Slovenia, climate changes are manifested in mild winters, hot and dry summers, and increasing frequency of occurrence of extreme weather phenomena. The rate of climate changes, however, is varied in different regions, depending on their individual features. In this context, it is of fundamental importance for particular communities to investigate the scale of environmental changes in their region of residence.

An element particularly sensitive to climate warming is temperature of surface waters, frequently treated as an indicator of such transformations (Adrian et al. 2009, Ptak et al. 2018). Due to its parameters, water rapidly responds to changes in the conditions of the surroundings, affecting among others its amount, quality, or physical parameters. Water temperature is considered as its basic parameter (Ptak, Nowak 2016). Water temperature is of key importance for the course of other processes occurring in rivers, both with biotic (Howell 2018) and abiotic

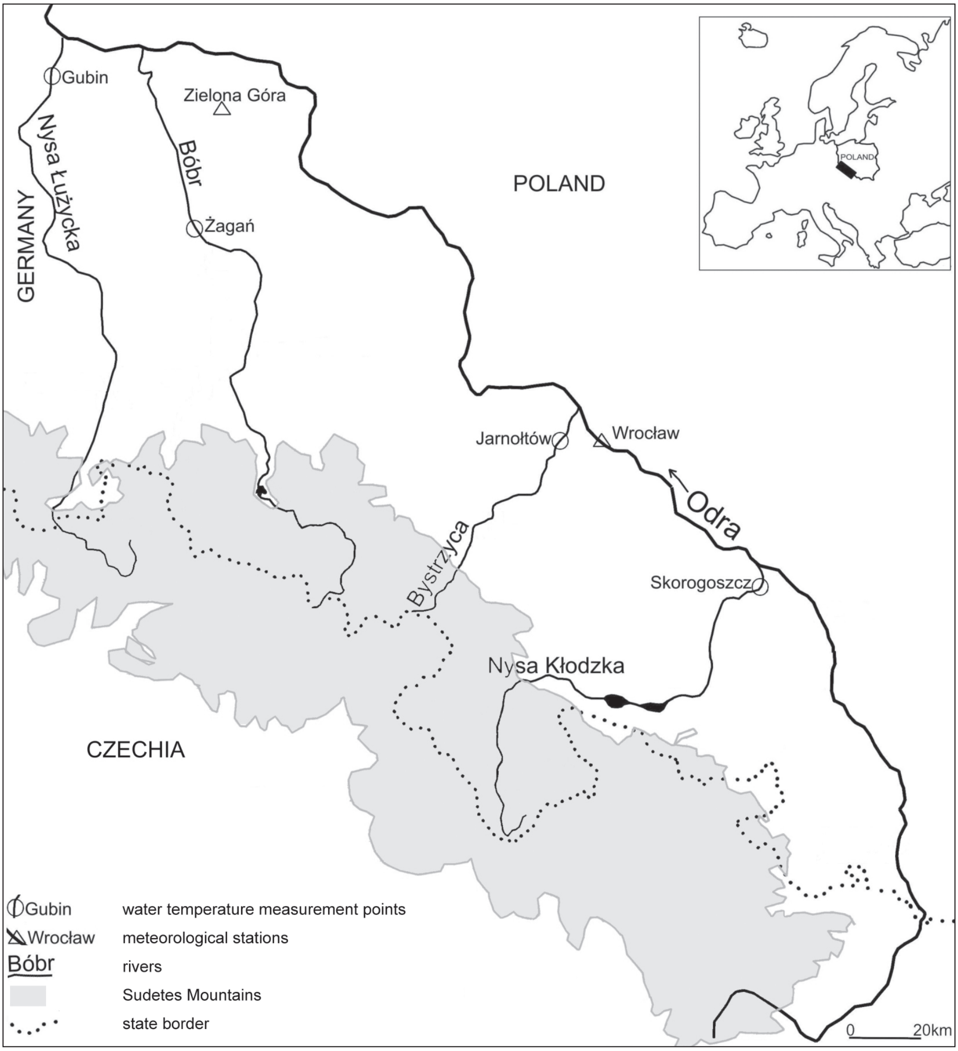


Fig. 1 – Location of the study area

(Rajwa-Kuligiewicz, Bialik, Rowiński 2015) character. Therefore, it is important to investigate the nature and scale of its fluctuations. Detailed knowledge on transformations of rivers in reference to particular regions for which water frequently constituted and constitutes the key element of development is of high importance. The majority of research concerning water temperature fluctuations in rivers conducted in different regions of the world (Floury et al. 2012, Caldwell et al. 2015, Basarin et al. 2016, Liu et al. 2018) shows an increasing tendency, particularly determined by climate changes. The situation is modified by human activity that can include wastewater inflows (Łaszewski 2018), construction of dams (Kędra, Wiejaczka 2018), and use of land in the catchments and on banks of rivers (Dugdale et al. 2018). Kaushal et al. (2010) emphasise that if the rate of increase in water temperature is maintained, it can considerably affect among others eutrophication, biological productivity, toxicity of contaminants, and loss of biodiversity of water ecosystems.

The objective of the paper is the analysis of thermal conditions of Sudetic rivers in Poland over the last several decades. The study objective was implemented in a two-fold approach. The analysis covered the determination of long-term tendencies of water level fluctuations, both at the annual and monthly scale, as well as their relations with air temperature.

2. Study area

The paper presents the analysis of water temperature fluctuations in four rivers (Fig. 1): Nysa Łużycka (length 252 km, catchment area 4,297 km^2), Bóbr (length 272 km, catchment area 5,876 km^2), Bystrzyca (length 92.2 km, catchment area 1,768 km^2), and Nysa Kłodzka (length 181.7 km, catchment area 4,565 km^2). The land use structure in the catchments is dominated by forest and agricultural land, with the following respective contribution for particular rivers: Nysa Łużycka: 44 and 45%, Bóbr: 45 and 50%, Bystrzyca: 22 and 68%, Nysa Kłodzka: 25 and 69%. Dam reservoirs are located on the discussed rivers – particularly on their middle and upper courses. The largest ones include: Otmuchów (20.6 km^2, Nysa Kłodzka), Nysa (20.0 km^2, Nysa Kłodzka), Mietków (9.3 km^2, Bystrzyca), Paczków (6.9 km^2, Nysa Kłodzka), and Pilichowice (2.4 km^2, Bóbr). Results of diagnostic monitoring performed by the Voivodship Inspectorate for Environmental Protection in Wrocław (Report 2010) show that all the analysed rivers were characterised by poor state of waters. Based on the Hyrographic Map of Poland it was determined that in terms of sewage supply, the least favourable situation occurred in the case of Nysa Łużycka, where discharge of municipal sewage occurred at a small distance from the measurement site. Inthe remaining cases, sewage discharges were located at a distance from several (Nysa Kłodzka) to z dozen kilometres (Bóbr, Bystrzyca) from the temperature measurement points.

All the rivers begin in the Sudetes, located in Central Europe in the territories of three countries: Poland, Czechia, and Germany. The mountains constitute a watershed for the Baltic, North, and Black Sea. The rivers discussed in the paper are direct tributaries of the Oder River, the second largest river in Poland, flowing into the Baltic Sea.

3. Data and methods

The paper is based on observations of the Institute of Meteorology and Water Management concerning water temperature in the aforementioned rivers. Four stations (Gubin, Żagań, Jarnołtów, Skorogoszcz) were selected due to the continuity of data for possibly long periods (1971–2014). Each of the analysed stations is the last one before the inflow of a given river to the Oder River. Water temperatures concern mean monthly and mean annual values. Moreover, data concerning air temperature fluctuations for two stations – Zielona Góra and Wrocław were used (Fig. 1). The statistical analysis was performed in accordance with assumptions adopted in the paper (Ptak, Choiński, Kirviel 2016) presented below.

The analysis of trends in measurements of mean annual water temperature in rivers was performed with the application of the Mann-Kendall test. It is based on the determination of the non-parametric coefficient of rank correlation of τ_b-Kendall for a given data series, and series of subsequent time steps t_i, $i = 1, \ldots, n$. Coefficient τ_b determined the strength of the monotonic correlation between two variables. Its value shows the amount by which the percent of all possible observations for which the direction of difference between them is the same for both variables is higher than the percent of observation pairs not showing such a correlation. It is calculated based on the S statistic determining the number of observation pairs not characterised by similar directions of differences for both of the analysed variables. It is determined based on the following formula:

$$S = \sum_{i>j} sign\,(X_j - X_i) sign(Y_j - Y_i) \tag{1}$$

Variance of S statistic is determined with consideration of the possibility of occurrence of correlated ranks, according to the following formula:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\,(t_p - 1)(2t_p + 5)\right] \tag{2}$$

Knowledge of the variances permits approximation of the distribution of S statistic with normal distribution due to its transformation into standard result Z. The transformation occurs according to the following formula:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, & if S > 0 \\ 0, & if S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}, & if S < 0 \end{cases} \tag{3}$$

The procedure described above permits testing the hypothesis on the occurrence of a monotonic trend. The zero hypothesis assumes lack of such a trend, and particularly random distribution of measurement values in time. The determination of the strength of correlation between mean annual water and air temperatures employed Pearson's coefficient of linear correlation *r*. The measurements for the Nysa Łużycka and Bóbr Rivers were correlated with measurements from station Zielona Góra, and from the Bystrzyca and Nysa Kłodzka Rivers with measurements from station Wrocław. Based on the calculated coefficients and their 95% confidence intervals, the range of the most probable percentages of variance common for both of the variables was determined.

4. Results

In the monthly cycle, no statistically significant correlations are observed in trends of water temperature fluctuations in the winter season. The strongest correlations are obserbed in summer (Table 1). The situation is similar in the case of air temperature, suggesting a strong correlation of both mediums. In the annual cycle, the most significant trends concern two rivers: Bystrzyca and Nysa Kłodzka, located in the eastern part of the analysed area. The course of mean annual water temperatures in the analysed rivers is presented in Figure 2.

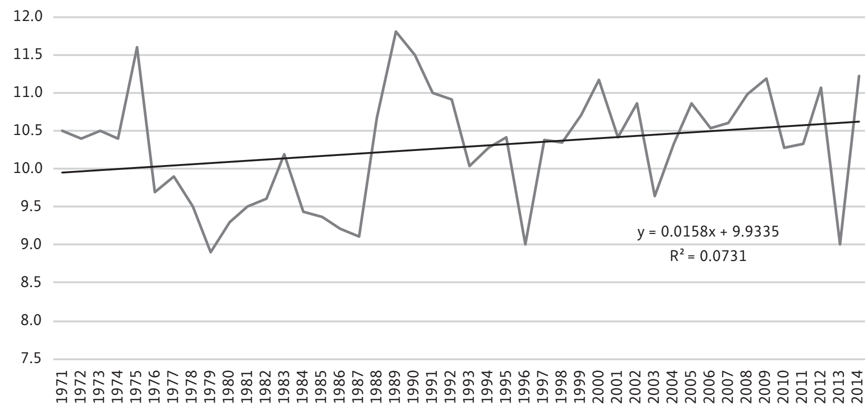
The analysis of the multiannual 1971–2014 shows that all four rivers were charaterised by low variability of mean annual water temperatures, equalling 1 °C. Nysa Łużycka and Nysa Kłodzka were the warmest (10.3 °C), and the remaining two,

Table 1 – Results of the analysis of annual and monthly trends of water and air temperatures for the analysed stations

	Water temperature				Air temperature	
	Nysa Łużycka	Bóbr	Bystrzyca	Nysa Kłodzka	Wrocław	Zielona Góra
Nov		*	*	*	*	
Dec						
Jan	+					
Feb	+					
Mar						
Apr	*	**	*	*	***	***
May	**	***	+	***	*	*
Jun	***	*	+	**	***	**
Jul	*	*		***	***	*
Sep	*	+	**	**	***	*
Aug	*	**	*		*	*
Oct	***	*	*		+	+
Year	*	**	***	***	**	**

*** if trend at α = 0.001 level of significance. ** if trend at α = 0.01 level of significance. * if trend at α = 0.05 level of significance. + if trend at α = 0.1 level of significance

(a)



(b)

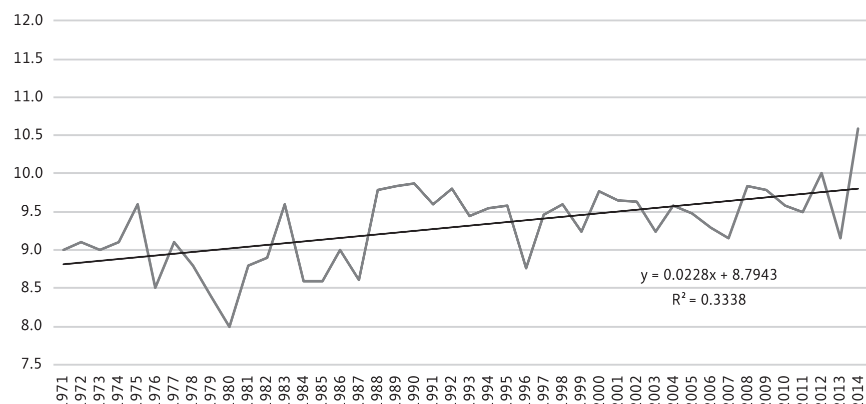


Fig. 2 (a, b) – Tendencies of water temperature fluctuations in Sudetic rivers in the period 1971–2014. Nysa Łużycka River (a), Bóbr River (b), Bystrzyca River (c), Nysa Kłodzka River (d).

namely Bystrzyca (9.5 °C) and Bóbr (9.3 °C), were slightly cooler. The course of water temperature in particular rivers was generally parallel towards each other. In the case of particulr years, certain differences were recorded for individual rivers in comparison to the remaining ones (e.g. in 1979, when an increase in water temperature was observed in Nysa Kłodzka, whereas in the remaining cases its decrease was observed, etc.), but such situations were sporadic. Over the period of the last four decades, an increase in temperature was recorded in all cases, varying from 0.15 °C · dec^{-1} to 0.33 °C · dec^{-1}. The highest recorded temperatures in the entire analysed period were variable, and ranged from 22 to 23.9 °C. At the seasonal scale, the coldest month was January, when mean temperature from the entire multiannual for Bystrzyca amounted to 1.7 °C, and the warmest month was July, when for Nysa Łużycka and Nysa Kłodzka the recorded mean temperature

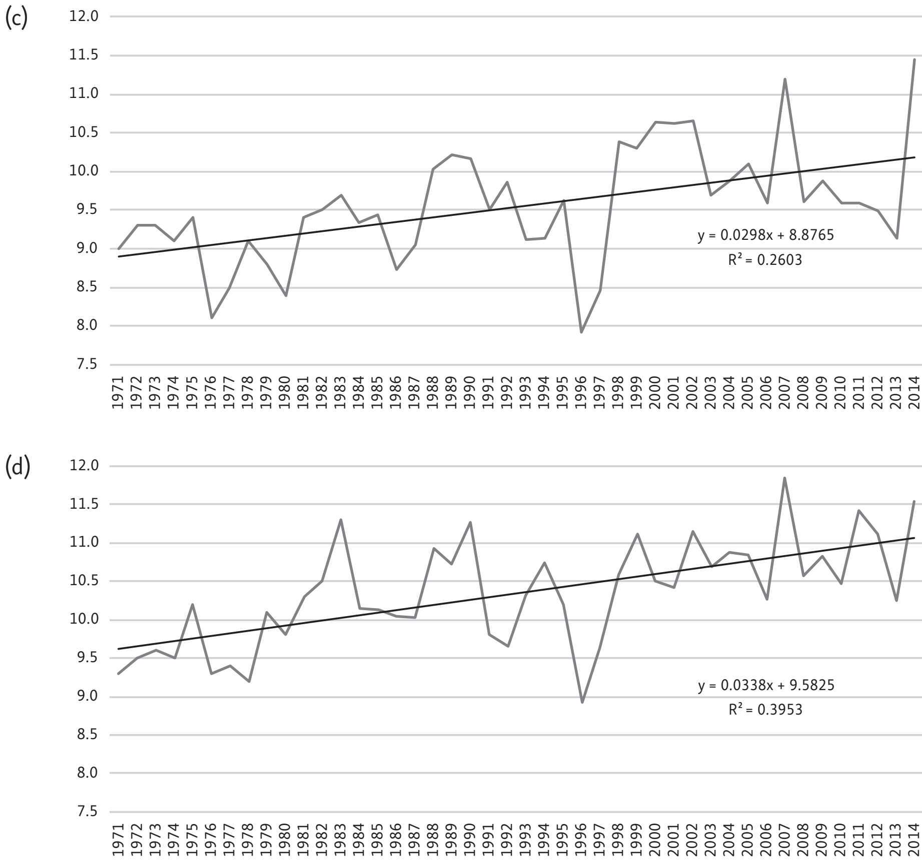


Fig. 2 (c, d) – Tendencies of water temperature fluctuations in Sudetic rivers in the period 1971–2014. Nysa Łużycka River (a), Bóbr River (b), Bystrzyca River (c), Nysa Kłodzka River (d).

was 19.1 °C. The highest increase in water temperature was observed in months of late spring and summer. In the case of Nysa Kłodzka, in July, in increased by 0.7 °C · dec^{-1}, and in May by 0.6 °C · dec^{-1}. Each time it was statistically significant. In the remaining cases, an increase in water temperature in particular months of the warm half-year was slightly lower. For Nysa Kłodzka, in May and July, it increased by 0.5 °C · dec^{-1}, and in June by 0.4 °C · dec^{-1}. Water temperature in Bóbr increased by the same value in April and May, and in Bystrzyca in August and October. Winter months also showed an increasing tendency, but its value was lower than that for the earlier period (mean increase at a level of 0.2–0.3 °C · dec^{-1}). Winter months were characterised by the lack of tendencies of changes, or in the case of Nysa Łużycka even negative tendencies, but they were not statistically significant.

5. Discussion

Changes in the thermal regime of rivers in the Fore-Sudetic region are in accordance with the commonly observed tendency of increase in surface waters. It is observed among others in other cases from Central Europe. In the case of rivers located in the territory of Slovenia, Frantar (2012) designated four regions based on thermal regime. He determined that considering two periods (1976–1990 and 1991–2005), an increase in water temperature occurred in all of them, varying from 0.7 °C to 1.3 °C. The increase was approximate to that for the rivers analysed in this paper. In the case of the Bela River in Slovakia, in the period 1959–2008, water temperature increased by 0.12 °C (Pekárová et al. 2011). In Latvia, analysis was performed concerning water temperature fluctuations in the warm half-year (May–October) in division into large, medium-sized, and small rivers (Latkovska, Apsite 2016). Based on data from 36 hydrological stations, increase in water temperature was determined to be prevalent (it concerned more than 72% of rivers). Based on the analysis of water temperature fluctuations in Latvian rivers in the warm half-year, Jurgelenaite, Kriaučiuniene, Šarauskiene (2012) determined that the greatest changes occurred in the period 1991–2010 and started from 0.04 °C · season^{-1}. The cause of the observed changes was successive climate warming, recorded in the course of air temperatures. The close relation between surface water temperature and air temperature is unquestionable (Ptak, Tomczyk, Wrzesiński 2018). Arora, Tockner, Venohr (2016), analysing rivers in the territory of Germany, emphasise that among all the considered hydro-climatic variables, air temperature was the primary factor affecting water temperature in rivers. In reference to the cases discussed in the paper, a similar conclusion can be drawn. Long-term water temperature increase in all rivers corresponded with the course of air temperature. The course of mean annual air temperatures in the analysed stations is presented in Figure 3. The determined Pearson coefficient of correlation r which in all cases equalled 0.8 suggests very high correlation of both variables.

The value is approximate to those in other studies, among others to results of analysis of correlations of water temperature and climate conditions in the Yongan River catchment in China (Chen et al. 2016), rivers in the coastal zone in Poland (Ptak, Choiński, Kirviel 2016), or in other lowland regions in Poland (Marszelewski, Pius 2016). In the context of relations with climate conditions, the turn of the 1980's and 1990's was characteristic. In the case of lakes in Central Europe, Woolway et al. (2017) determined a considerable increase in mean annual water temperatures in the late 1980's as a response to rapid climate changes. In the case of rivers, changes in the period were observed by among others Hari et al. (2006), Bonacci, Trninić, D., Roje-Bonacci (2008), or Hrdinka et al. (2015) for rivers in the south of the Sudetes. Water temperature in the analysed rivers also showed a respone to the observed changes. After 1990 it was higher by an average

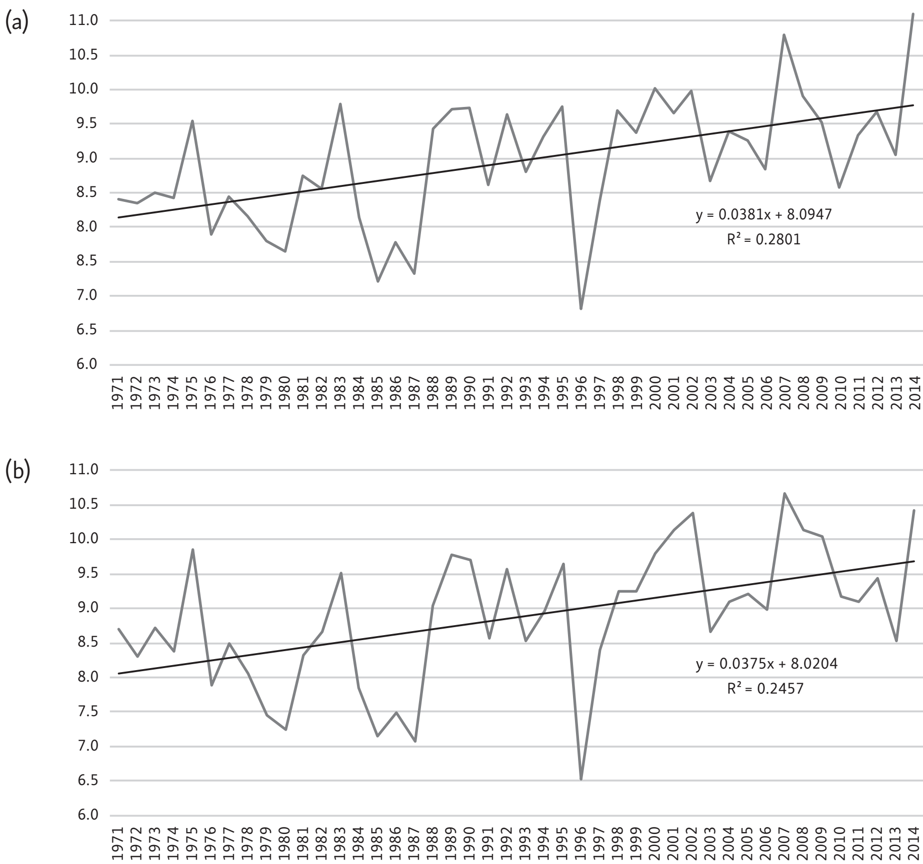


Fig. 3 – Air temperature fluctuations, annual mean values for stations. Wrocław (a), Zielona Góra (b).

of 0.8 °C in comparison to the first period. Moreover, it is worth emphasising that mean annual water temperatures from the 1990's until today have been sporadically lower than the average determined for the entire study period.

The remaining, lower contribution of effect on water temperature in a river should be associated to individual parameters. The scale of effect of climatic factors on water temperature fluctuations in a river is modified by local parameters, including among others land use structure in the catchment, effect of human activity, etc. The complexity of factors determining water temperature in rivers was presented by Webb, Nobilis (1995) referring to the territory of Austria. The authors observed an increase in water temperature in the 20th century determined by intensifying human activity. Regulation of the main rivers was reflected in an increase in mean water temperature in autumn (reduced discharge). Moreover, different tendencies were dependent on the presence of lakes, sewage discharge, or occurrence of milder winters in the recent period. The Sudetes and Fore-Sudetic region are characterised by the presence of numerous dam reservoirs. As emphasised by Olden and Naiman (2010), discharge regulation by means of dams has a direct effect on the thermal regime of rivers, but in the case of the analysed rivers, the factor did not determine their thermal conditions, and the key role evidenced above was played by climatic factors. The situation can be explained by the location of dams in reference to observation sites. Dam reservoirs are mainly located in upper and middle sections of the discussed rivers (among others in order to facilitate flood protection), and profiles for which observations were conducted are not located in their direct vicinity. Therefore, changes in thermal conditions become obscure along the course of the river. Another important factor besides the climatic one can be land use in the catchment. In the case of the analysed region, all rivers showed an increasing tendency of water tempretaure, but their scale was variable. The slowest rate was recorded for Nysa Łużycka and Bóbr, probably due to the forest cover of their catchments. Both rivers flow through one of the largest forest complexes in Poland, namely Bory Dolnośląskie (approximately 1,650 km²). Forest catchments have a characteristic thermal regime (Webb, Crisp 2006). Based on research conducted in Denmark, Kristensen et al. (2015) determined that even the shortest sections of near-bank forest reduced water temperature by 1 °C in comparison to the temperature of open space. Based on measurements of water temperature performed in three streams in Luxembourg, Dohet et al. (2015) determined that river bank forests evidently alleviated winter minimums, summer maximums, and thermal variability. Based on research conducted in the United States, Justice et al. (2017) evidenced that the combination of introducing forest cover on river banks and hydrotechnical works allowed for a considerable reduction of water temperature in the summer period, which can substantially balance changes resulting from climatic conditions. In reference to the analysed area, earlier studies conducted on smaller rivers (Czerna Wielka and Szprotawa) showed a significant impact of forest cover in the catchment on water temperature distribution (Ptak 2017). In the case of the Czerna Wielka River (with a higher forest cover), mean water temperature was 8.0 °C, whereas in the case of Szprotawa (forest cover lower by approximately half) it was 9.2 °C. The greatest differences between the rivers were observed in the vegetative season (May–October), where mean temperatures equalled 12.1 °C and 14.7 °C, respectively.

The observed changes in the thermal regime of rivers constitute and will constitute the primary factor of transformations of such ecosystems, especially that future simulations show a further increase in water temoerature (Van Vliet et al. 2013, Hardenbicker et al. 2017). Ducharne (2008) determined that water warming in Seine resulted in a decrease in dissolved oxygen and an increase in phytoplankton biomass in the growth period. The effect of temperature increase on the hydrobiological conditions is an important issue. As emphasised by Punzet et al. (2012), many freshwater organisms are limited by certain thermal ranges. Extreme temperature fluctuations can lead to the loss of biological diversity. The obtained results suggest that all such threats concern Sudetic rivers.

The assessment of water quality in the analysed rivers (in accordance with the guidelines of the Framework Water Directive 2000/60/EC) refers to Bodies of Surface Water, and in such designations it reveals their poor condition (Report 2015). Such a situation causes restrictions of the optimum use of rivers in the discussed region by different branches of the economy (increased costs of water treatment, unattractive colour and smell of water for recreational purposes, etc.). The implementation of protection tasks should involve not only the reduction of supply of pollutants, but also the reduction of the effect of climate changes on an increase in water temperature in rivers, and as a consequence on the worsening of unfavourable physical and chemical water parameters. In the context of the observed climate warming (Wrzesiński et al. 2015, Kolář, 2017, Milošević et al. 2017, Tomczyk 2017), it is important to develop solutions for a reduction of their negative effect. Measures with a global range are optimal, e.g. reduction of greenhouse gas emission. As observed in recent years, however, such an approach is not feasible for economic reasons and the related policies of particular countries. Due to this, solutions mitigating effects of climate change should be sought at the regional or local level. In the case of thermal regime of rivers, such solutions include among others buffer zones in the bank zone in the form of presence of vegetation. The recorded relatively fast increase in water temperature in Sudetic rivers makes it necessary to implement measures contributing to a reduction of this unfavourable phenomenon. The implementation of such a concept could be based on e.g. proper management of river banks (forestation). Such measures, however, can be difficult to implement for many reasons. According to Kilianová et al. (2017), issues of land use in flood areas of rivers are constantly subject to geographic research, because they are of economic and ecological importance. In addition to the above premises, among others those with a potential effect on the thermal regime of a given river should be considered. Reaching a consensus on the subject requires the involvement of interdisciplinary works on many levels, covering not only a strictly scientific, but also administrative and legal approach.

6. Conclusion

The paper refers to one of the most serious problems of the modern world associated with climate change. The occurring transformation has evident effects on different components of the environment, and particularly surface waters. Due to the strong dependence between air and water temperature, an increase in the value of the former proportionately affects the latter (with certain disturbances determined by local factors). Such a situation was observed in the case of rivers of the analysed Fore-Sudetic region, where in the period of the last four decades, an increase in air temperature was recorded, followed by an increase in water temperature. The observed situation can be considered as very unfavourable in the context of water management in the discussed region. Already currently, the waters of the analysed rivers show poor quality according to the assessment of Bodies of Surface Waters. Further increase in water temperature, affecting its many other physical and chemical parameters, can lead to a deterioration of the state. Due to this, measures aimed at the reduction of the unfavourable situation at the regional level are necessary, e.g. through the aforementioned solutions applying buffer zones.

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