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Long-term water temperature fluctuations in coastal rivers (southern Baltic) in Poland

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Abstract. The paper presents water temperature fluctuations in coastal rivers (Rega, Parsęta, Słupia, Łupawa, Łeba) located in the southern Baltic Sea area in Poland. Based on the available detailed data on daily values of the analysed characteristic in the years 1971–2015, tendencies of changes in the period were determined. It includes an analysis of temperature fluctuations in reference to mean annual and mean monthly values. In all of the five cases, the mean annual temperature showed an increasing tendency. The value of water warming in particular rivers was approximate, and ranged from 0.26 °C·dec^{-1} to 0.31°C·dec^{-1}. At the monthly scale, the highest increase was recorded in April, and amounted to 0.46°C·dec^{-1} on average. Water temperature fluctuations were particularly determined by climatic changes, and strongly correlated with air temperature. Local factors characteristic for coastal rivers, i.e. presence of infrastructure of small water power plants and predominance of groundwater alimentation, had a secondary effect on changes in the thermal regime of the analysed rivers.

Key words:
river,
water temperature,
climate warming,
coastal,
Baltic

Introduction

Research concerning climatic changes (Cermak et al. 2000; Bednorz and Kossowski 2004; Tavartkiladze et al. 2012; Pavlik et al. 2014; Matuszko and Węglarczyk 2015) and closely related hydrological conditions (Nõges et al. 2010; Schmidtko et al. 2014; Choiński et al. 2015; Wang et al. 2015) has been particularly popular over the recent decades. Water temperature fluctuations are considered as indicators of global warming by many authors (Dąbrowski et al. 2004; Thompson et al. 2005; Arai 2009). The observed changes in the aforementioned elements have and will have serious consequences in the functioning of inland water ecosystems – both rivers and lakes. This can be related to many aspects, including the biological (Balcombe et al. 2011; Pełechata et al. 2015) and the physical-chemical (Milana et al. 2013; Zhang et al. 2015), or issues related to human life (Phung et al. 2015; Breisinger et al. 2016).

In spite of the rich common knowledge on water temperature fluctuations in rivers and lakes, due to among others the aforementioned facts it is important to expand the body of knowledge with regard to particular objects or geographical regions. Such an approach is not only justified in strictly scientific terms, but can also find practical application.

Regions located in the vicinity of seas and oceans are particular. In the case of Poland, as emphasised by Cieśliński (2006), the coastal zone of the southern Baltic Sea is an exceptionally valuable place, not only in terms of economy, but also due to the unique character of the natural environment. This specificity attracts the interest of researchers from various fields of science. Research conducted there concerns geomorphological issues (Mazurek 2010; Major 2011; Kostrzewski et al. 2015) and climatic issues (Świątek 2011; Kolendowicz and Forycka-Ławniczak 2013; Tomczyk and Bednorz 2014), among others. Papers concerning rivers and lakes located in the southern coastal belt of the Baltic Sea are abundant (Siwek et al. 2001; Ficek et al. 2011; Obolewski and Glińska-Lewczuk 2013; Szpikowski et al. 2015; Woszczyk 2016). Publications regarding the hydrology of the area, however, evidently lack modern information on one of the main characteristics of waters, namely temperature.

The objective of the paper is the assessment of changes in the thermal regime of five rivers in the coastal zone of the southern Baltic Sea located in Poland. It includes an analysis of temperature fluctuations in reference to mean annual and mean monthly values.

Moreover, the objective of the paper is the assessment of the scale of transformations and their correlation with climatic and local factors.

Study area, material and methods

The study area covers the southern coast of the Baltic Sea with an area of 15,500 km^2, constituting approximately 5% of the area of Poland. Its boundary in terms of hydrographic division is a first-order watershed, particularly constituting a belt of terminal moraines of the Pomeranian phase of the Last Scandinavian Glaciation. The watershed separates catchments of coastal rivers from the catchments of the Vistula and Odra Rivers – the two largest rivers in Poland. The evident influence of the Baltic Sea on climatic conditions is observed in the analysed area. According to the Atlas… (1994) the continentalism index (determined based on the annual analysis of air amplitude) in Poland varies from 38% to 52%, showing the lowest values in the coastal zone.

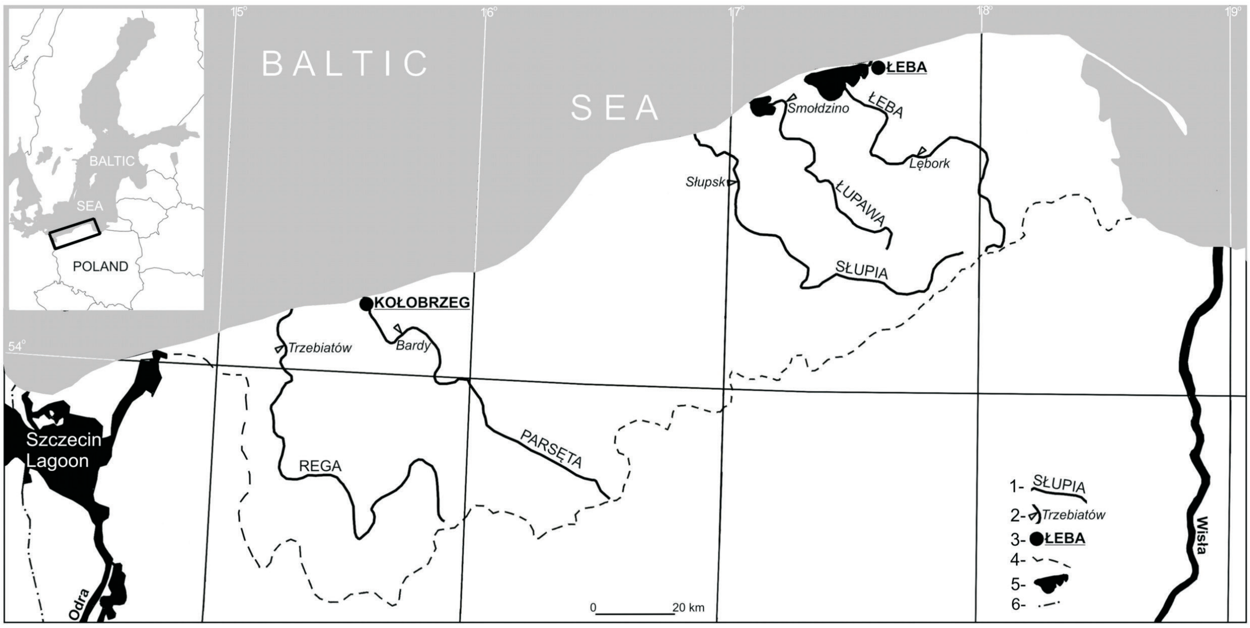

Fig. 1. Location of the study area and objects. 1 – rivers, 2 – water temperature measurement site, 3 – meteorological station, 4 – watershed of the first order, 5 – lakes, 6 – boundary

The detailed analysis of long-term water temperature fluctuations concerns five rivers, namely: the Rega, Parsęta, Słupia, Łupawa, and Łeba (Fig.1).

The Rega River is the longest of the rivers (172 km), and the Łupawa is the shortest (98.7 km), also having the smallest catchment (924.5 km^2). The largest catchment is that of the Parsęta River (3,151 km^2). A hydrological description of coastal rivers was presented by Florek (2008) stating that they are very similar to one another. The comparison suggests among others that although the rivers are abundant in water, they have even outflows throughout the year, with amplitudes of water stages in the upper courses amounting to approximately 0.5 m, and approximately 3 m in the lower courses.

The study was based on data concerning measurements of the surface temperature of riverine waters, performed daily at 7:00 (GMT +1) by the Institute of Meteorology and Water Management (IMGW) in the years 1971–2015. For each of the rivers, 16,425 records were collected. Such information provided the basis for the analysis of mean annual and mean monthly temperatures for all of the rivers. For the purpose of determination of changes in climatic conditions, expressed in changes in air temperatures, data were applied for the meteorological stations at Kołobrzeg (54°10'N, 15°34'E) and Łeba (54°47'N, 17°33'E) for the same period 1971–2015 (also collected by IMGW). Moreover, the paper applied groundwater temperatures for the Resko station (also observed by IMGW) with limited availability for the years 1972–1983.

The analysis of trends in measurements of mean annual water temperature in rivers was performed with application of the Mann–Kendall test. The calculations were performed in the R package. It is based on the determination of the non-parametric coefficient of rank correlation of τb-Kendall for a given data series, and series of subsequent time steps *ti, i = 1, … , n*. The coefficient τ_b determines the strength of the monotonic correlation between two variables. Its value shows the amount by which the percentage of all possible observations for which the direction of difference between them is the same for both variables is higher than the percentage 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.

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 Rega and Parsęta Rivers were correlated with measurements from the Kołobrzeg station, and from the Słupia, Łupawa, and Łeba Rivers with measurements from the Łeba station. 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.

The significance of trends was verified in reference to the previously assumed level $\alpha = 0.05$.

Results

The Mann–Kendall test shows significant results in the case of all of the five rivers. This means that an increase in mean annual water temperatures occurred in the study period. The strength of the effects measured by means of coefficient τ_b was similar in all of the cases, and varied from 0.42 to 0.52. The highest increase was recorded for the Rega River, amounting to 0.31°C·dec^{-1}, and the lowest for the Słupia River, amounting to 0.26°C·dec^{-1}. Water temperature fluctuations are presented in Figure 2.

In the monthly distribution (of the average for all of the rivers), the highest increase was recorded in April (0.46°C·dec^{-1}). No tendency was recorded for, among others, December and February. No decreasing tendency was recorded for any month.
A considerable transformation of the thermal regime of coastal rivers is associated with climatic changes. The performed analysis of air temperature for Kołobrzeg and Łeba stations confirms this assumption, evidencing its substantial increase (Fig. 3).

Analyses of mean annual temperatures in the Rega and Parsęta Rivers showed a very strong correlation with mean annual air temperatures measured at Kołobrzeg station. Approximate results were also obtained in reference to correlations of mean annual temperatures in the Słupia, Łupawa, and Łeba Rivers with measurements from station Łeba. The confidence intervals of coefficients of determination r^2 show (from 75 to 84%) that depending on the river, water temperature fluctuations co-occur with changes in air temperatures. Moreover, the analysis of cross-correlation plots, showing the level of correlation of measurement of annual water temperature in rivers with air temperature, suggests that the strongest correlation occurs between measurements for the same year. Correlation between measurements from various years is considerably weaker, and in comparison to the strength of correlation between measurements for the same year it can be considered as omitted.

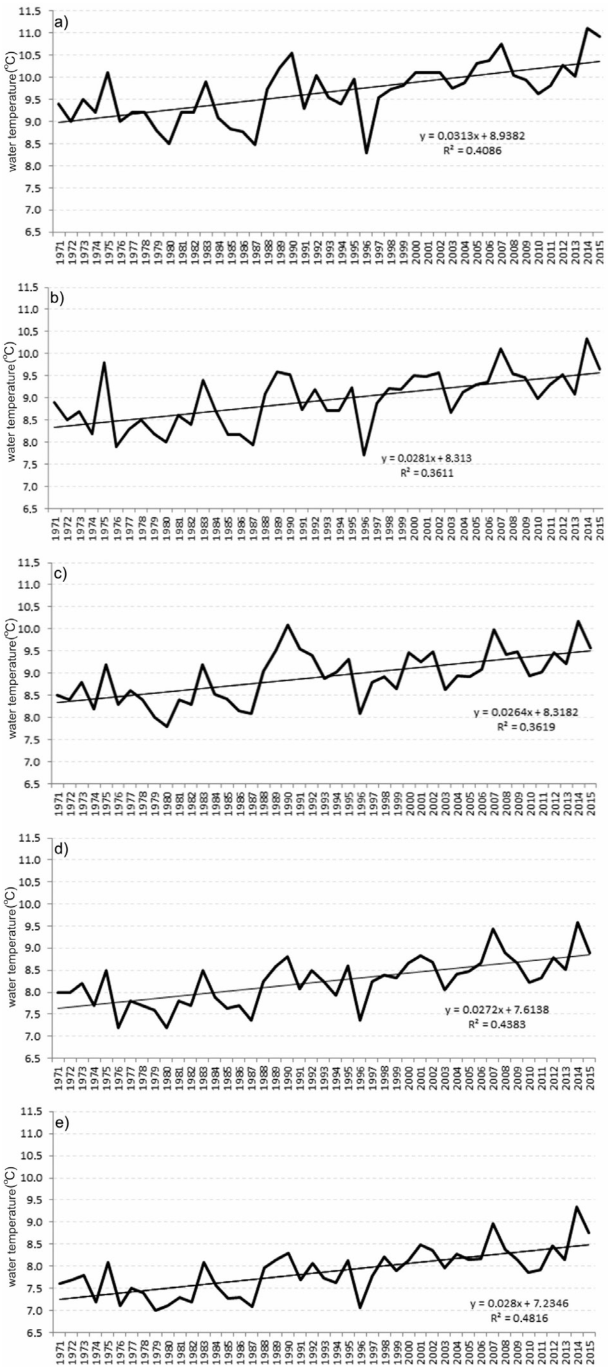

Fig. 2. Water temperature fluctuations in coastal rivers in the years 1971–2015 (annual means); a) Rega, b) Parsęta, c) Słupia, d) Łupawa, e) Łeba

Discussion

The results presented in the paper suggest that over the last 45 years, considerable transformations occurred in the thermal regime of all the analysed rivers. They show a high increase in temperature in the period, amounting to approximately 0.28°C·dec^{-1}. Such a situation is primarily caused by the observed climatic changes, as evidenced by an increase in air temperature for two stations analysed in the paper, and strong correlations with water temperature. Certain local conditions are also worth attention.

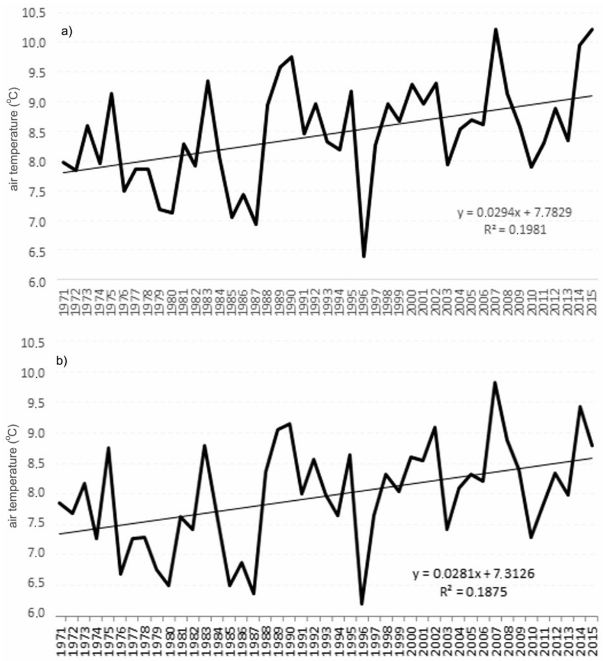

Fig. 3. Air temperature fluctuations (annual means) in the years 1971–2015; a) Kołobrzeg, b) Łeba

According to Piotrowski et al. (2015), they can be determined by natural, semi-natural, and anthropogenic processes. The study area is distinguished by the presence of small water power plants and groundwater alimentation of rivers.

Water temperature fluctuations in rivers are common, and have been recorded in various areas of the world. Žganec (2012), analysing temperature fluctuations in three rivers in Southern Europe (Croatia), determined their increase over a period of several decades. The highest increase was recorded for the Mrežnica River. In the years 1953–2008, it amounted to 0.48°C·dec^{-1}. In the case of the United States, Kaushal et al. (2010) studied 40 streams and rivers (in various time periods). The authors determined that 20 of them were characterised by a significant increase in water temperature, ranging from 0.09 to 0.77°C·dec^{-1}. In the territory of Austria, Webb and Nobilis (2007) analysed water temperature fluctuations in three rivers: Salzach, Traun, and Danube in the years 1901–2000. It was determined that in all of the cases, an increase in the fluctuations occurred, amounting to approximately 1.5°C on average. In the case of the Baltic zone, a detailed analysis of the issue was performed by Jurgelėnaitė et al. (2012) based on 84 rivers in Lithuania. According to the study, the highest increase in water temperature (0.04°C) occurred in the last period, i.e. in the years 1991–2010.

Results referring to air temperatures are in accordance with other studies of the type performed in the southern region of the Baltic Sea in other periods. Michalska (2011), analysing air temperatures among others for the Ustka station, located in the study area, determined that in the years 1951–2005 it increased by (0.28°C·dec^{-1}). A more extensive analysis of air temperature fluctuations on the Polish coast was presented by Tylkowski (2013). Based on data from seven stations, the author determined that air temperature on the Polish coast in the years 1966–2009 increased by 0.3°C·dec^{-1} on average. The increasing tendency of temperature has also been recorded in other regions of the Baltic zone (Lizuma et al. 2007; Klavins et al. 2009; Russak 2009).

The performed analysis of correlation between air temperature and water temperature shows that the former depends on the latter – for all of the five rivers it was 79.5% on average. The remaining percentage is associated with other factors – including, as mentioned before, human economic activity and alimentation conditions of rivers. Chen et al. (2016) determined the effect of air temperature fluctuations and human activity on water temperature fluctuations in the catchment of the Yongan River in China. According to the study, they are 75% determined by climatic changes, and the remaining percentage corresponds with human activity. The percentage is approximate to that for rivers analysed in this paper. Many papers refer to correlations of water temperature in rivers with factors other than climatic factors (Le Blanc et al. 1997; Kinouchi et al. 2007; Hester and Doyle 2011). Poole and Berman (2001) consider activity related to the production of electric energy as a factor of importance to changes in water temperature. This finding is confirmed among others in reference to rivers in NW Spain (Álvarez-Troncoso et al. 2015), or in the case of research conducted in the Rhone River in the Alps (Fette et al. 2007). In Poland, coastal rivers (except for mountain rivers) can be considered as belonging to the most favourable locations for water power plants, as determined by their natural characteristics. In the upper courses of the sections, numerous inclinations occur, reaching 7‰ (Florek 2008). The existing dams were particularly constructed at the turn of the 20th century (Radtke et al. 2012). They are distinguished by a low increase in water stages (Babiński et al. 2015). Jarosiewicz and Obolewski (2013) presented the effect of small water power plants on the hydrological conditions (including water temperature) of the Słupia River – according to the authors the river best used for energy engineering purposes in Central Pomerania. Daily water temperature fluctuations below the power plant amounted to approximately 0.5°C. Furthermore, the authors determine that water temperature fluctuations in the Słupia River are particularly determined by climatic conditions.

Coastal rivers are distinguished in the hydrographic network of Poland by their hydrological regime. It was established as even with the spring flooding and groundwater rainfall, and nival alimentation (Dynowska 1972). As further emphasised by the same author, the relatively permeable Pleistocene formations can absorb considerable amounts of water. This is of importance in periods of drought, when rivers are abundantly fed by groundwaters. According to Paszczyk (1975), in the case of coastal rivers, groundwater alimentation is their dominant form of alimentation. In addition to the effect on water outflow parameters, the type of alimentation can also determine its other parameters, including among others thermal dynamics (Tung et al. 2014; Higashino and Stefan 2016). Cooling of riverine waters by the groundwaters feeding them is observed in the case of the Rega and Parsęta Rivers, where the increase in water temperature in the years 1971–2015 was 0.4°C lower than air temperature for the Kołobrzeg station. This finding is confirmed by monitoring of groundwater temperature conducted for station Resko in the years 1972–1983. Mean temperature of groundwaters in the period amounted to 8.8°C, and temperature in the Rega River (near which it is located) in the analogical period equalled 9.2°C. Water temperature for rivers: Słupia, Łupawa, and Łeba increased at the same rate as air temperature for the Łeba station.

Conclusions

The analysis of water temperature fluctuations in coastal rivers in the region of the southern Baltic Sea performed in the paper suggests a strong transformation of the thermal regime over the last 45 years. For five of the analysed cases, water temperature in the period increased by between 0.8 and 1.2°C. The highest increase in temperature in the analysed period was recorded in April. It amounted to more than 2°C (on average for all of the rivers). Such a situation particularly reflects climatic changes, and is in accordance with many studies of the type in various parts of the world. The recorded increase in air temperature for two stations located in the study area strongly correlated with water temperature. Other specific features of coastal rivers, namely the application of their water resources by small power plants, and substantial contribution of groundwater alimentation, can be recognised as factors of secondary importance.

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