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Influence of a lake on river water thermal regime: a case study of Lake Sławianowskie and the Kocunia River (Pomeranian Lakeland, Northern Poland)

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ABSTRACT. Water temperature is one of the basic physical parameters of rivers and lakes. Rising temperature can transform these ecosystems over a broad range of factors (water mixing, water quality, biological conditions, etc.). In the case of rivers, their thermal regimes also can be modified by local conditions (e.g., tree cover, adjoining water bodies, etc.). In this paper, we address the functioning of the river-lake system in northern Poland (Kocunia River-Lake Sławianowskie) in terms of the effect of the lake on temperature conditions in the river. Dependencies in daily water temperatures between stations located above and below the lake were assessed with linear regression. Based on daily morning water temperatures for the period 2012-2017, it was determined that water temperature in the river below the lake was higher than at the measurement site located above the lake by an average of 1.1°C. The greatest differences were recorded in summer-autumn months when average monthly downstream water temperatures were as much as 3.9°C higher than upstream water temperatures. This phenomenon is an example of a local factor (the lake) magnifying global factors, i.e. rising temperatures associated with climate change. The information in this paper can provide future reference for decision makers and state institutions with responsibility for measures aimed at reducing the effects of climate change.

KEYWORDS: River-lake system, water temperature, measurement data.

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1. INTRODUCTION

Lakes are important elements of the natural environment, shaping its character both in their direct vicinity and throughout their catchments (affecting the hydrological conditions, microclimate, etc.). They are landscape-forming elements, and guarantee biodiversity (Ptak et al. 2013). Due to their strong ability to accumulate energy and matter, the presence of lakes contributes to the mitigation of extreme hydrological situations (droughts and floods, among others). Direct relationships between lentic and lotic waters are evident where lake deltas form, as exemplified by Lake Płociczno (Chudzikiewicz et al. 1979), among others. Lakes also fulfill important roles in the transport of various dissolved and particulate substances as they circulate in the catchment. The accumulation of materials in lake sediments can change properties of the river above and below the lake. Such a situation is referred to by Hillbricht-Ilkowska (2005), among others, in the case of the functioning of river-lake systems in northeast Poland. Temperature is one of the basic physical properties of surface waters. This parameter largely determines the functioning of many lake and river ecosystems. The occurrence, course, and scale of many processes (e.g., duration of the ice season, water mixing, solubility of different kinds of substances, etc.) have strong correlations with water temperature. Water temperature is a fundamental element of hydrobiological conditions. The diversity of the flora and fauna, the abundance within species, and where and when they occur depend on the thermal regime.

One of the most serious problems faced by humanity today is climate change (Nowak, Ptak 2018; Nowak, Ptak 2019; Ptak et al. 2018; Ptak et al. 2019b). In this context, it seems important to reduce greenhouse gases, thus inhibiting further increases in air temperature. Such action will inhibit transformations of all other closely related components of the natural environment (including water temperature). At the global scale, such measures require international arrangements, which are not always possible in the current geopolitical environment. Therefore, it is important to determine local factors that can affect thermal conditions of surface waters (Ptak 2018).

This paper addresses the assessment of Lake Sławianowskie's impacts on the thermal conditions of the Kocunia River in northern Poland.

2. MATERIALS AND METHODS

Thermal conditions were analysed in the Kocunia River, which flows through Lake Sławianowskie in the Pomeranian Lakeland in northern Poland (Fig. 1). The length of the river segment analysed is 41 km; its catchment area is 171 km^2. This section of the river is characterised by a low gradient. Its channel width does not exceed several meters, and depth varies, depending on the hydrological situation, from 12 to several tens of centimetres (Fig. 2). The morphological parameters of Lake Sławianowskie are as follows: surface area 277.6 ha,

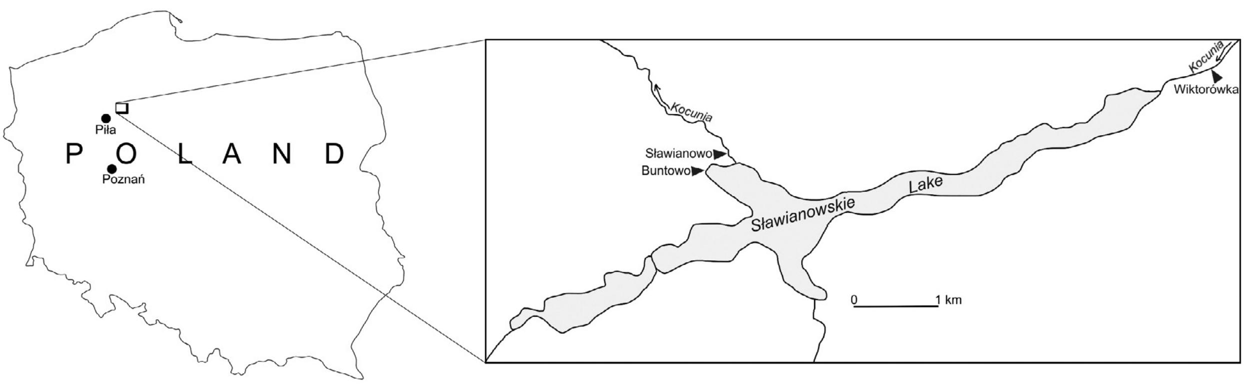

Fig. 1. Location of study object

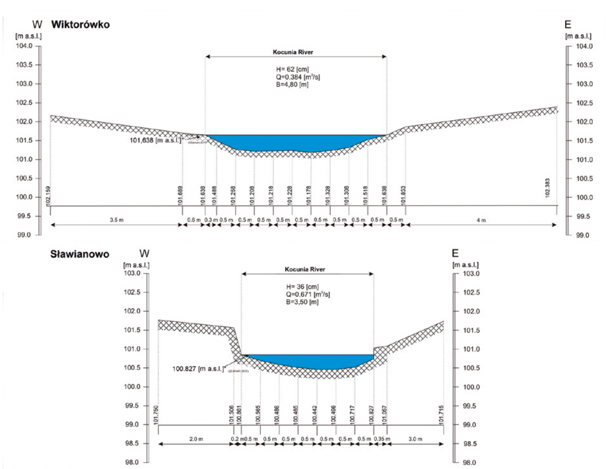

Fig. 2. Cross-sections through the Kocunia River channel in profiles at Wiktorówko and Sławianowo performed on 22.01.2015 (based on data from IMWM-NRI)

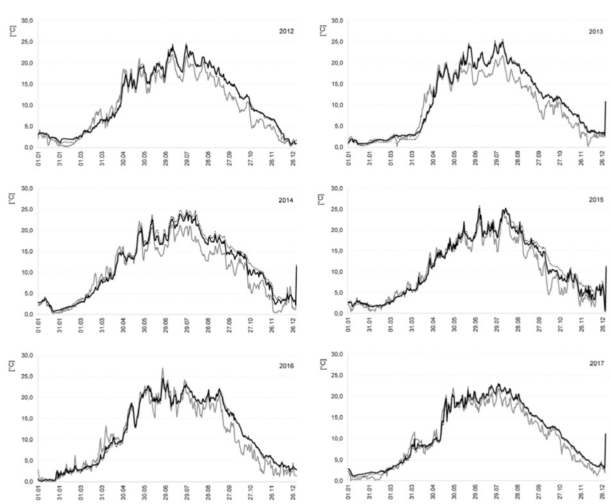

Fig. 3. Time series of water temperature in Lake Sławianowskie (dotted line), the Kocunia River at the inflow to the lake (grey line), and at the outflow from the lake (black line) in the years 2012-2017 (based on data of IMWM-NRI)

water volume 18.3 million m^3, maximum depth 5.0 m, mean depth 6.6 m. The lake, with the characteristics of a channel, is composed of two basins separated by narrows with a bridge crossing. The western basin is smaller, shallow, and strongly overgrown with rushes. The eastern basin is strongly elongated, deeper, and includes two bays reaching north and south, so that the lake resembles a cross (Fig. 1). The inflow of the Kocunia River to the lake is located at its eastern end; the outflow is at the end of the northern bay. The lake is surrounded by a narrow belt of a mixed tree stand, and further by extensive agricultural land (WIOS 2003).

Water temperature was measured at three water gauge stations of the Institute of Meteorology and Water Management, National Research Institute (IMWM-NRI). Two of the gauges (Wiktorówko and Sławianowo) are located on the Kocunia River (500 m above the lake and 160 m below the lake, respectively), and one (Buntowo) is located on the northern part of the lake (Fig. 1). The measurement series covered calendar years 2012-2017. The measurements were performed at 6.00 AM by means of an OTT Orpheus Mini Water Level Logger at the river stations, and by an observer at the lake station. Measurement sensors were located in the vicinity of water gauges in limnometric columns. The sensors were immersed at a depth of 40 cm from the water surface. Data readout and device operation control took place once a month.

Air temperature used in this study was taken from the synoptic station of IMWM-NRI in Piła, approximately 30 km south of the study area. The measurements were carried out manually in a meteorological cage at a height of 2 m above the surface. Relationships between water temperatures at the three stations were examined with linear regression and R software (*lm* function) (Daròczi 2015).

3. RESULTS

Among the three sites of water temperature measurement, the site at the inflow to the lake showed a pattern different from the others (Fig. 3 and 4). This contrast is associated with the course of the Kocunia River through Lake Sławianowskie, which causes transformation of the physical parameters of water carried by the river (including water temperature, among others) into those characteristics of the lake. In the multi-annual period of our analysis, average annual differences in water temperature in the Kocunia River above and below Lake Sławianowskie varied from 0.9 to 1.4°C (Fig. 4). Over a multiyear monthly scale, average differences in water temperature varied from –1.3 to 2.7°C (Table 1). On a monthly scale, average differences in water temperature varied from –2.6 in April 2013 to 3.9°C in August 2014 (Table 1).

Analysis of the comparisons in Table 1, along with the course of variability of daily temperatures in the river and lake (Fig. 3), indicates a two-fold character of the dynamics of water temperature in the Kocunia River measured above and below Lake Sławianowskie over an annual cycle. The smallest differences are recorded in winter and spring months when they do not exceed 1.3°C; from January to March they are less than 0.5°C (Fig. 4). In the colder half of the year, water temperature frequently depends on the occurrence of ice (both in the river and lake). When ice is present, there are smaller thermal contrasts between stations under both lentic and lotic flow conditions. It is also important that during spring, temperatures at the outflow are lower than at the inflow to the lake (Figs. 4 and 5). In the summer-autumn months, in most cases (almost 70%), average monthly differences between outflow and inflow temperatures are higher than 2.0°C (in the extreme case, August 2016, the difference reached 3.9°C (Table 1). In summer, water in the near-surface layer of Lake Sławianowskie is heated faster than that in the Kocunia River above the inflow to the lake. The river temperature is influenced by its sources, i.e. surface runoff and groundwater. According to Chomutowska and Wilamowski (2014), river water temperature changes very fast in comparison to still waters (lakes, ponds), depending on air temperature, groundwater temperature, and springs feeding the river, among other factors. Above the first measurement site (approximately 0.6 km), there is a strongly overgrown flow-through lake with an area of 5 ha. Water flowing through the shaded surface of the lake is subject to a slower heating process. A similar situation is described by Bielak (2014), among others, referring to swamps overgrown with reed beds around Biebrza, participating in the alimentation of the river. Alimentation with (colder) groundwater is important during summer, when water resources in the catchment are successively exhausted.

Water temperatures in Kocunia at the Wiktorówko and Sławianowo stations were strongly correlated (0.92 and 0.88, respectively) with air temperature (station Piła). The correlations suggest that air temperature plays the key role in the thermal regime of the river, although it is lower in the case of the station below the outflow from Lake Sławianowskie (Sławianowo). In this context, the calculated correlation between surface temperature in Lake Sławianowskie and the observation site on Kocunia located below it was almost perfect: 0.997 (r^2 = 0.994) (Fig. 6). This tight correlation reflects the fact that water flowing in the river 160 m below the lake still shows properties of lake waters in terms of temperature.

Temperature measurements (2012-2017) in the Kocunia River at the inflow to Lake Sławianowskie (Wiktorówka), and at the outflow (Sławianowo), were compared using a linear regression analysis. The results confirmed the dependence of the outflow temperature (explained variable) on the inflow temperature (explanatory variable) at a level of significance of <0.001. The regression equation was y = 0.74 + 1.04 x, where y is the outflow temperature and x the inflow temperature (r^2 = 0.945, $p = 2.2 \cdot 10^{-16}$). This result suggests that water temperature in the Kocunia River is higher at the outflow from Lake Sławianowskie than at the inflow.

4. DISCUSSION

The issue of thermal relationships between lentic and lotic waters has been frequently addressed in the context of reservoirs (Poirel et al. 2010; Maheu et al. 2016; Wiejaczka, Wesoły 2017; Jiang et al. 2018). Deep water reservoirs with a bottom outlet cause an increase in water temperature in rivers in winter, and a decrease in summer (Olden, Naiman 2010). Different patterns apply to shallow reservoirs: during the warm months, an increase in water temperature in rivers below dams is observed (Lessard, Hayes 2003). Differences in water temperature in Julianpolka in southern Poland were determined by Wiatkowski (2008), where temperature was higher by an average of 2.4°C at the site below the reservoir. Łaszewski (2015), analysing the effect of reservoirs on the temperature of the Jeziorka and Rządza Rivers (vicinity of Warsaw) in the summer season, determined that there was a considerable increase in average monthly values below the reservoirs. In the case of Lubrzanka (Świętokrzyskie Mountains, southern Poland), significant differences were observed throughout the study period between water temperature above and below the existing reservoir (Kozłowski 2017). Water in the river below the weir was on average 3.2°C higher than above the reservoir, and the great-

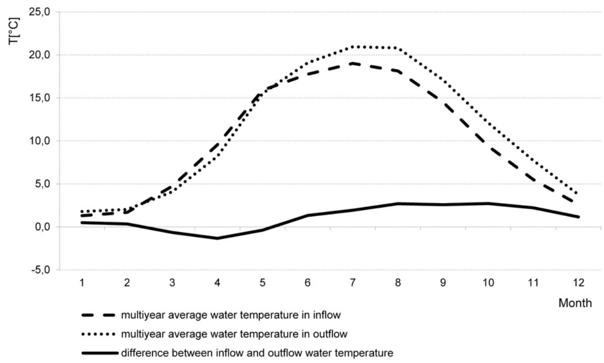

Fig. 4. Multiyear monthly average water temperature of the Kocunia River at the inflow and outflow of Lake Sławianowskie 2012-2017 (based on data of IMWM-NRI)

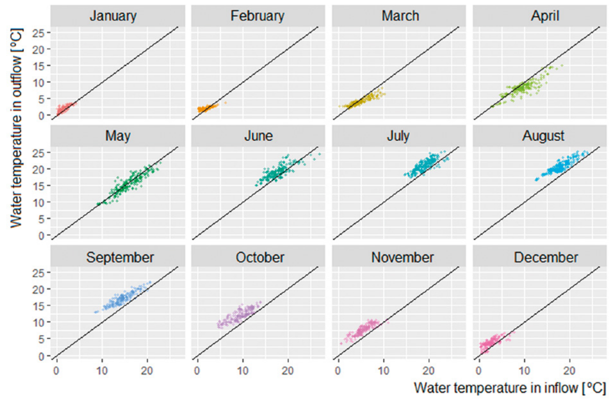

Fig. 5. The relationship between the inflow and outflow of water temperature of Lake Sławianowskie for each month during the period 2012-2017

Table 1. Average monthly differences in water temperature [°C] in the Kocunia River between stations located at the outflow and inflow from the lake (based on data of IMWM-NRI)

Month	Year						Average
	2012	2013	2014	2015	2016	2017	
January	0.8	−0.1	0.4	0.5	0.3	1.0	0.5
February	1.1	−0.1	0.0	0.3	−0.2	1.0	0.3
March	−1.1	0.5	−1.2	−0.7	−0.9	−0.5	−0.6
April	−1.2	−2.6	−1.4	−0.9	−1.5	−0.5	−1.3
May	−0.2	−0.3	0.1	−0.4	−0.5	−1.0	−0.4
June	1.7	2.4	2.0	0.8	0.6	0.6	1.3
July	2.2	3.2	2.4	1.5	0.4	1.8	1.9
August	2.4	3.5	3.9	2.1	1.9	2.3	2.7
September	2.7	3.2	2.7	2.2	3.0	1.7	2.6
October	2.9	2.4	2.7	3.2	3.4	1.7	2.7
November	2.3	2.6	2.6	1.4	2.6	2.0	2.2
December	1.0	1.4	1.3	0.8	1.1	1.3	1.2
Average	1.2	1.4	1.3	0.9	0.9	0.9	1.1

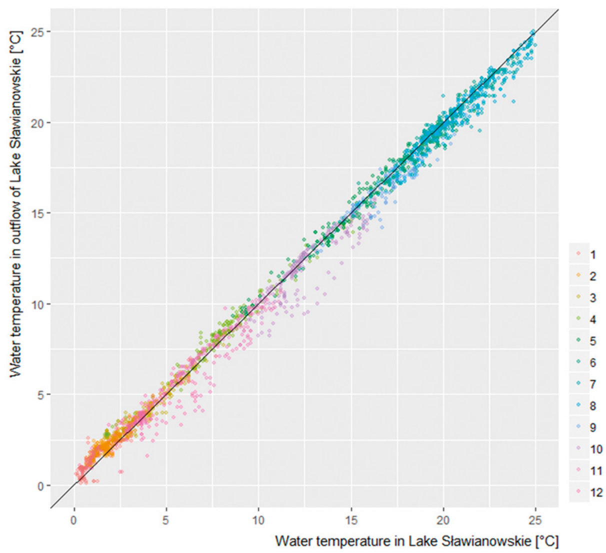

Fig. 6. The relationship between the surface and outflow water temperature of Lake Sławianowskie by month during 2012-2017

est difference in temperature (4.3°C) was recorded in August. According to the study, water temperature in the river below the weir in each of the analysed months was higher below the reservoir than above it.

The results reported here are consistent with the studies summarized above. Although the lake we studied has no typical polymictic parameters, i.e. thermal variability observed in the deepest place of the lake in the summer season (Fig. 7), the hypolimnion is thin, and the zone with the greatest depth (more than 10 m) occupies only about 25% of the lake volume (Choiński et al. 2013). Due to the shallow depth of the Kocunia channel at the outflow from the lake (Fig. 2), water from the near-surface zone, usually heated to a greater degree than the deeper parts of the lake, is discharged first.

This study corresponds with the global research trend, popular over recent decades (Ptak, Nowak 2016; Ptak et al. 2018; Martinsen et al. 2019; Ptak et al. 2019a; Zhu et al. 2019), concerning the thermal conditions of surface waters, both lotic and lentic. In a broader context, it is also related to the course of ice phenomena on rivers and lakes. The great majority of the numerous studies analysing thermal conditions of surface waters (Hampton et al. 2008; Schneider, Hook 2010; O'Reilly et al. 2015) points to changes in thermal regimes, and particularly increases in water temperature. These changes apply in Poland, where average temperature in 14 lakes increased by 0.43°C·dec^{-1} over the past four decades (Ptak et al. 2018). In the case of rivers outside mountainous areas, an increase from 0.17 to 0.27°C was observed (Marszelewski, Pius 2016). In the zone directly adjacent to the Baltic Sea, the warming varied from 0.26°C·dec^{-1} to 0.31°C·dec^{-1} (Ptak et al. 2016). Moreover, the duration and extent of ice cover on rivers has declined (Ptak, Choiński 2016; Choiński et al. 2015; Nowak et al. 2018). These dynamics point to the complexity of potential consequences of changes in thermal conditions of flowing waters, which will intensify over the next several decades (Czernecki, Ptak 2018). Detailed monitoring of the thermal regime of surface waters should be undertaken, along with measures aimed at slowing the heating of lake waters, as postulated by Ptak et al. (2018), among others. In documented cases, such measures could involve a change in the land use structure in the catchments or direct vicinity of rivers. Forested riparian zones and a high percentage of forest cover in catchments can contribute to lower water temperatures, as documented by Ptak (2017), among others, in the case of two rivers in southern Poland.

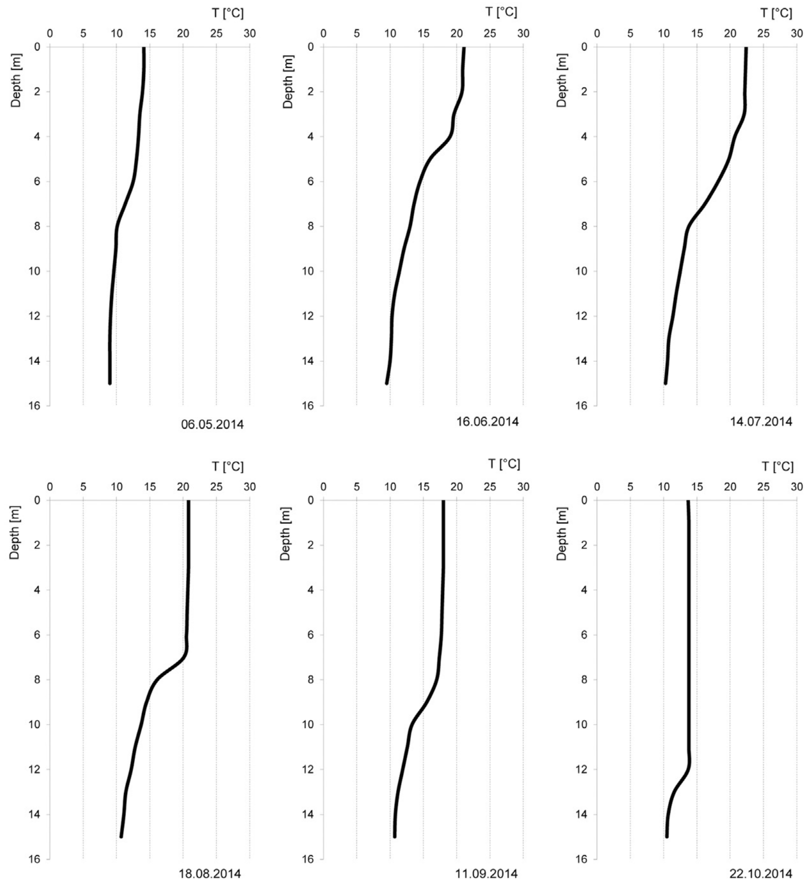

Fig. 7. Example thermal profiles in Lake Sławianowskie in the warm half of the year 2014 (based on data from IMWM-NRI)

5. CONCLUSIONS

We analysed water temperature in the Kocunia River-Lake Slawianowskie system. The observations showed that the lake affects the thermal regime of the Kocunia River by increasing its water temperature below the lake for most of the year (Fig. 4). Only in the period from February to May are the water temperatures at the lake outflow slightly lower than the water temperatures at the lake inflow. Differences between the measurement sites on the river located above and below the lake in the multi-annual period show that below the lake, average annual water temperature was higher by an average of 1.5°C. In the monthly cycle, the greatest differences occur in summer and autumn months, particularly in September and October, when on average they exceeded 4.0°C multiple times. The study corresponds with other studies showing that artificial shallow-water reservoirs increase temperatures in rivers flowing through the reservoirs (Lessard, Hayes 2003; Wiatkowski 2008; Łaszewski 2015). In this study, the same role was observed in the case of a natural lake with developed thermal stratification. The local dynamics of water temperature need to be considered in the context that they intensify the global factors that cause increasing air temperature and consequently, water temperature. Information included in this paper can provide the basis for future reference for persons or state authorities responsible for measures aimed at the reduction of effects of climate change.

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