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ANALYSIS OF WATER TEMPERATURE FLUCTUATIONS IN LAKE JAMNO

Mariusz Ptak[1]*, Mariusz Sojka[2], Adam Choiński[1]

[1] *Department of Hydrology and Water Management,*
Adam Mickiewicz University,
Krygowskiego 10, 61-680 Poznań, Poland
[2] *Institute of Land Improvement, Environmental Development and Geodesy,*
Poznań Life Science University,
Piątkowska 94, Poznań, Poland
**e-mail: marp114@wp.pl*

Abstract

The paper presents the analysis of thermal conditions of coastal Lake Jamno. The long observation series (1971-2013) for the course of surface water temperature suggests its considerable warming (0.28°C·dec-1). In the monthly cycle, an increase in surface water temperature is observed in all cases except for the winter period (December, January, February). Water was heated the fastest in April (0.58°C·dec-1) as well as May and September (0.46°C·dec-1). Mean annual air temperature increased at a similar rate (0.27°C·dec-1), but the coefficient of correlation of both media equalled 0.40. This suggests that other factors could contribute to the change in surface water temperature. One of such factors could be marine water intrusions. The strongest positive correlations of water temperature in Jamno and water level in the Baltic Sea occurred in the cold half-year, and negative in the warm half-year. From 2013, on the canal connecting Lake Jamno with the Baltic Sea, a storm gate was constructed that altered many processes and phenomena occurring in the lake so far. The paper covers the natural (quasi-natural) period of functioning of the lake, and provides a point of reference for future research on its thermal regime considering among others the effect of human pressure in the form of hydrotechnical infrastructure.

Key words: water temperature, climate change, coastal lake

INTRODUCTION

More than 7,000 lakes are located in Poland, representing more than 20 genetic types (Choiński 2007). The most peculiar ones include meteorite, mountain, or coastal lakes. Due to their specificity, each of the groups has been subject to many studies (Girjatowicz 2003, 2011, Obolewski et al. 2015, Wrzesiński et al. 2016, Choiński and Ptak 2017, Obolewski and Bąkowska 2017, Obolewski et al. 2018). Certain issues, however, still remain unclear. One of them is certainly the response of lakes to the effects of global warming, particularly evidently observed in recent years. One of the key parameters of lake ecosystems is water temperature (Skowron 2011, Ptak et al. 2018a). It is difficult to find a process not depending of that parameter. This can be referred to among others physical-chemical (Xu et al. 2012, Yang et al. 2018) or biological parameters (Pełechata et al. 2015, Roubeix et al. 2017) of water bodies. In this context, the further part of the paper focuses on Lake Jamno – one of several Polish coastal lakes. The specificity of coastal lakes can be discussed in several aspects. The first one concerns different (in comparison to the remaining part of the country) climatic conditions. The next one involves morphometric parameters of the lakes – large surface area and small depths. The most characteristic feature of this group of lakes is their direct hydraulic connection with the Baltic Sea, enabling inflow of marine waters with different physical and chemical parameters.

The objective of the paper was to characterise thermal conditions in Lake Jamno, including among others the determination of long-term monthly and annual directions and rate of surface water temperature fluctuations. The paper also presents the analysis of short-term water temperature fluctuations in the daily cycle. The paper covers the period from 1971 to 2013, i.e. until the moment of construction of the storm gate on the outflow from the lake. Year 2013 will constitute a point of reference (over the next decades) for the assessment of its effect on water temperature distribution in the analysed lake.

MATERIALS AND METHODS

The paper is based on two sets of data. This permitted the analysis of thermal conditions in Lake Jamno in two aspects – firstly in reference to long-term changes, and secondly in the short-term daily cycle. The analysis of directions and rate of surface water temperature fluctuations was performed based on mean monthly and mean annual water and air temperatures in the years 1971-2013. The analysis of short-term surface water temperature dynamics was based on daily water and air temperatures and daily water stages in the Baltic Sea for the years 1987-2013. The choice of research terms depended on the availability of data in the Central Base of Hydrological Data. The research material used in the paper was obtained from the Institute of Meteorology and Water Management, in the case of air temperature for station Koszalin located approximately 5 km from Lake Jamno, and for water stages in the Baltic Sea for station Kołobrzeg located approximately 35 km from Lake Jamno. The analyses were presented in the context of hydrological years, i.e. from 1 November to 31 October of the following year. The analysis of directions of surface water temperature and air temperature fluctuations in the years 1987-2013 in the monthly and annual cycle was performed by means of a non-parametric Mann–Kandall test (MK) (Kendall and Stuart 1966). Values of monthly and annual surface water temperature fluctuations in the lake and air temperature fluctuations were determined by means of a non-parametric Sen test (Gilbert 1987). The analysis of trend significance was performed for four levels of p_{α}: 0.1; 0.05; 0.01, and 0.001. Moreover, the paper presents a detailed analysis of daily water and air temperature fluctuations in reference to particular months and hydrological years. The values and directions of daily surface water temperature and air temperature fluctuations in the years 1987-2013 were evaluated adopting an analogical procedure as in the case of long-term analyses (Mann–Kendall and Sen test). The analysis of daily surface water temperature fluctuations in Lake Jamno was performed in reference to daily air temperature fluctuations and water level fluctuations in the Baltic Sea. The correlation analysis employed an (advance) time step of air temperature and water stage from 0 to 10 days, respectively.

STUDY AREA

Lake Jamno is located in northern Poland in the coastal belt (Fig. 1). The lake is fed by two rivers: Dzierżęcinka and Unieść. The surface area of Lake Jamno is 2,231.5 ha, mean depth 1.4 m, maximum depth 3.9 m, and volume of water accumulated in the lake basin equals 31.5 milions m^3 (Choiński 2006). According to Miotk-Szpiganowicz et al. (2007), the lake bottom is flat and covered with muddy sediments. The mutual influence of Lake Jamno with the Baltic Sea was disturbed in 2013 by the construction of a storm gate on Nurt Jamneński. Cieśliński (2016) emphasises that at the moment of blocking any inflow from the side of the sea, the lake was devoid of the supply of approximately 30 million m^3 of water annually. According to Cieśliński (2016), the primary and most evident effect of the constructed storm gate is a change in the qualitative state of the waters in Lake Jamno, and particularly a change in concentrations of indicators determined by the sea, e.g. electrolytic conductivity.

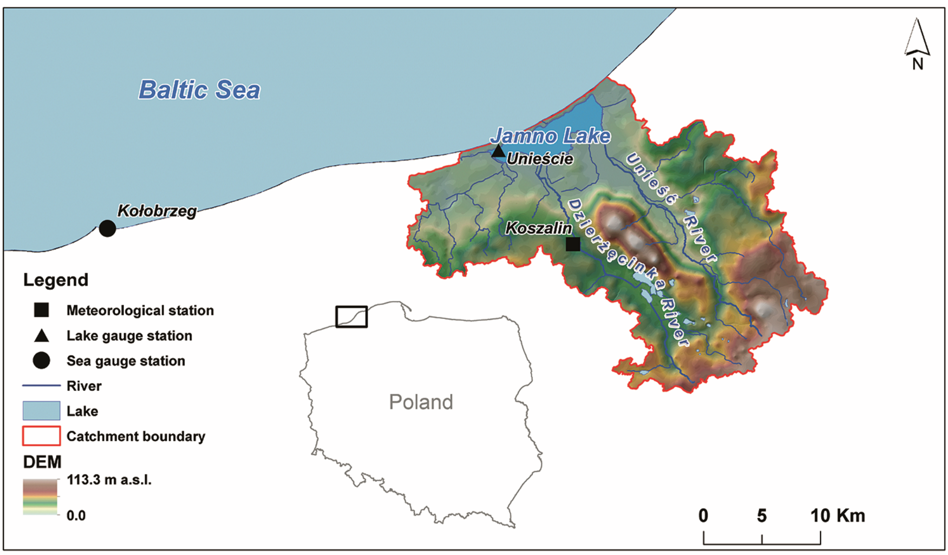


Fig. 1. Location of the study object

RESULTS AND DISCUSSION

Mean annual surface water temperature in Lake Jamno in the years 1971-2013 equalled 9.40°C. The warmest month was July (19.10°C), and the coldest – January (1.40°C) (Fig. 2).

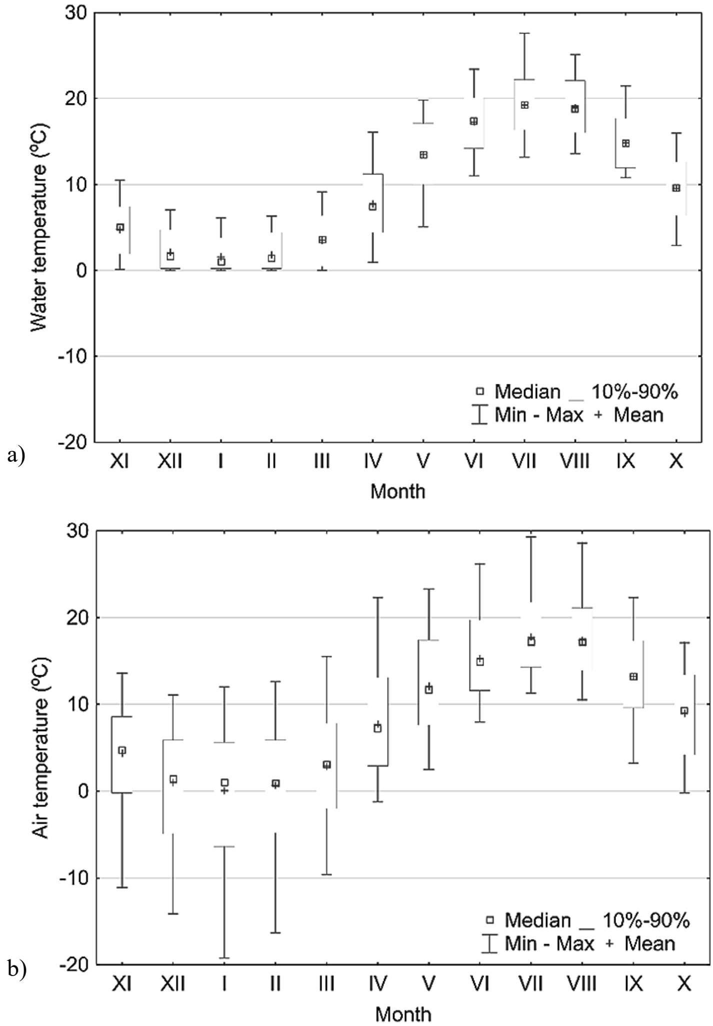


Fig. 2. Mean monthly surface water temperatures in Lake Jamno (a) and mean monthly air temperatures in station Koszalin (b)

Over the last four decades, mean annual surface water temperature in Jamno increased by 1.15°C. Over the last decade, mean annual temperature was higher than 9.40°C (Fig. 3). The increase in mean annual surface water temperatures generally observed in the years 1971-2013 was approximate to mean annual air temperatures (in both cases, the temperature trends were statistically significant at a level of 0.01).

In contrast to the commonly known dependency of surface water temperature on air temperature (Dąbrowski et al. 2004, Skowron 2009), however, the correlation of both media is relatively low, and equals 0.42. Different directions of changes are observed among others for 1972, 1982, 1990, 1991, 1994, 1996, 2001, and 2008 (Fig. 3). Therefore, factors exist that in spite of the polymictic character of Jamno contribute to the weakening of the impact of air temperature on surface water temperature. This is suggested by e.g. marine water intrusions, inflows of water with physical-chemical parameters different than those of the lake water from the catchment (the city of Koszalin with approximately 100,000 residents is located several km above the lake), or supply of heat released from sediments with considerable thickness deposited on the bottom. Bieniek et al. (2013) analysed the lithology and chemical composition of sediments of a core with a length of 4 m. No evident boundary exists between water and bottom sediments. Based on measurements performed in Lake Gopło, Grześ (1978) determined that the layer of bottom sediments in which important annual changes in temperature occur has a thickness of approximately 3 m, and from the point of view of heat processes is an integral part of the lake. Heat accumulated in bottom sediments in the summer period largely affects the thermal regime of the lake in the ice period. In the above context, the issue of heat exchange between sediments and water in Jamno is an interesting issue that would require thorough investigation in the future.

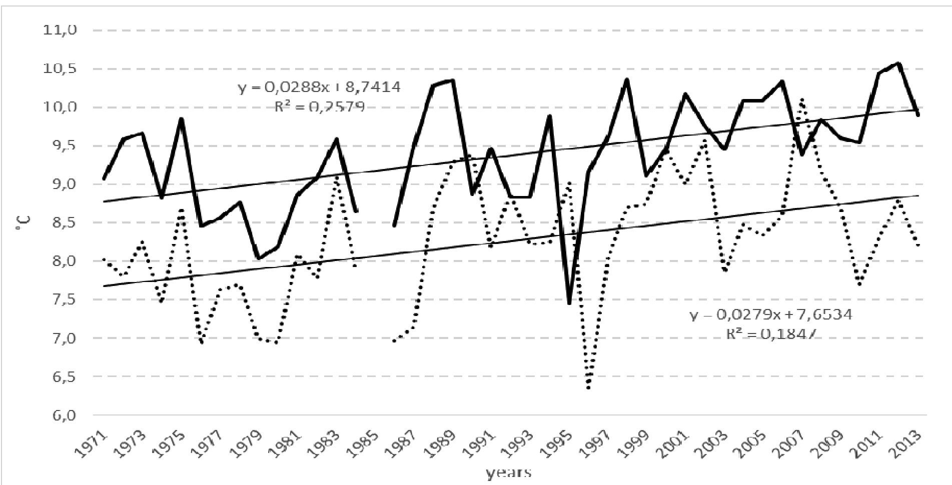
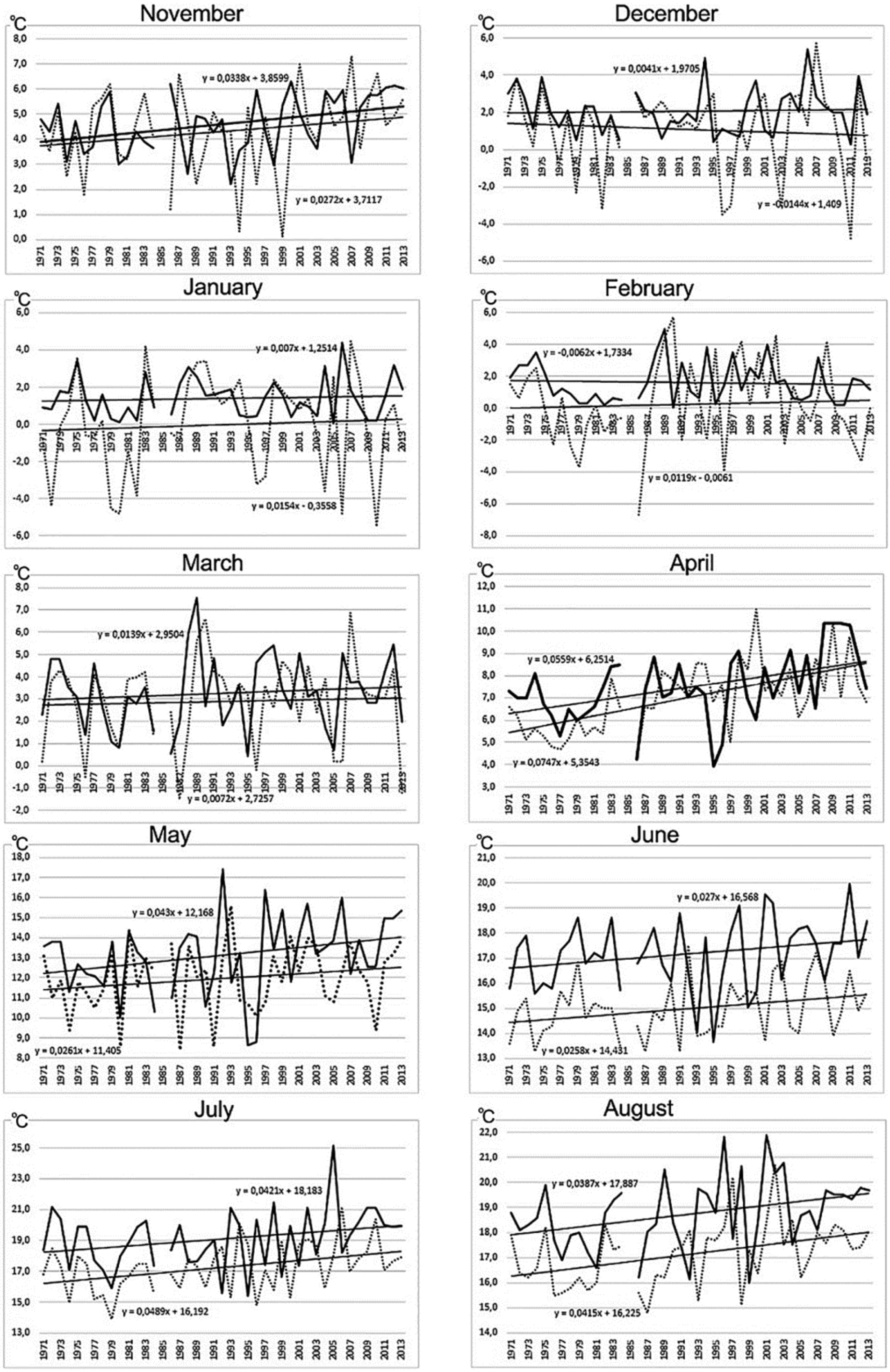


Fig. 3. Course of surface water temperature in Jamno (solid line) and air temperature for station Koszalin (dotted line)

In the monthly cycle, considerable surface water temperature fluctuations (warming) occurred except for December, January, February, March, and June (Fig. 4). The highest increase in surface water temperature was observed in April (0.56°C·dec^{-1}) as well as in May and July (0.43°C·dec^{-1}) (0.42°C·dec^{-1}). The analysis of mean monthly air temperatures showed that they increased in April, June, July, August, and September. The greatest changes, similarly as in the case of surface water temperatures, occurred in April (0.75°C·dec^{-1}).


November
y = 0,0338x + 3,8599
y = 0,0272x + 3,7117
December
y = 0,0041x + 1,9705
y = -0,0144x + 1,409
January
y = 0,007x + 1,2514
y = 0,0154x - 0,3558
February
y = -0,0062x + 1,7334
y = 0,0119x - 0,0061
March
y = 0,0139x + 2,9504
y = 0,0072x + 2,7257
April
y = 0,0559x + 6,2514
y = 0,0747x + 5,3543
May
y = 0,043x + 12,168
y = 0,0261x + 11,405
June
y = 0,027x + 16,568
y = 0,0258x + 14,431
July
y = 0,0421x + 18,183
y = 0,0489x + 16,192
August
y = 0,0387x + 17,887
y = 0,0415x + 16,225

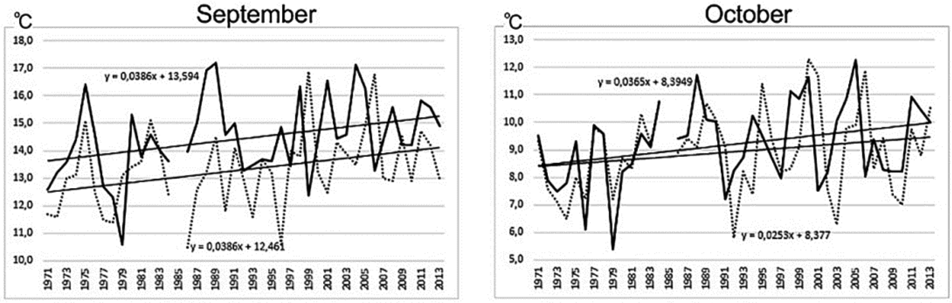


Fig. 4. Monthly tendencies of surface water temperature fluctuations in Jamno (solid line) and air temperature fluctuations for station Koszalin (dotted line)

A more detailed approach referring to daily water and air temperature distribution (Fig. 5) shows their similar course, however with certain shifts.

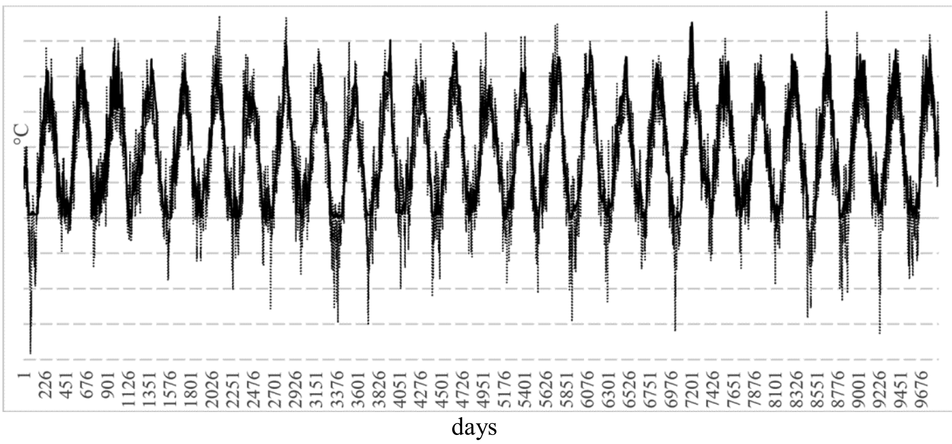


Fig. 5. Course of daily surface water temperatures (Jamno) and air temperatures (Koszalin) in the years 1987-2013

In his analysis of correlations between water level in coastal lakes and the adjacent marine waters, Girjatowicz (2008) determined that highly statistically significant correlations are the strongest in the cold half year (November-April). Positive correlations of surface water temperature in Jamno and water level in the Baltic Sea were the strongest in January, February, and March, and negative in July and August. This situation in the context of surface water temperature in Jamno suggests that an increase in water levels in the sea contributes to an increase in surface water temperature in Jamno (marine water in the aforementioned months is warmer in comparison to the cooled shallow lake). In summer, colder marine waters intruding into the heated water mass of Jamno will cause a decrease in its temperature (as confirmed by the obtained correlations).

Mutual correlations between water stages in the Baltic Sea and Jamno would be completely transparent if not for a factor disturbing them. Before the construction of the gate on Nurt Jamneński, the factor was its temporary obstruction caused by clastic material transported by littoral currents or ice dams. The same concerns correlations between water temperatures in the Baltic Sea and Jamno. The aforementioned correlations can be described as random events. Unfortunately, not many field observations are available that would involve the analysis of occurrence of long-term obstruction. One of rare works in the scope is the collection of observations performed by Schmidt (1967). In the years 1964-1965, the author performed systematic observations of water stages in Nurt Jamneński. Moreover, Gałka (1980) performed the analysis of the effect of water stages in the Baltic Sea on water stages in Jamno for the years 1951-1970. Wegner (1980) attempted the determination of the effect of Baltic waters on surface water temperatures in Jamno in the period 1961-1970. Choiński (2016) determined discharges between Jamno and the Baltic Sea in selected summer-autumn seasons for the years 1978-2010. The analysis of the aforementioned papers suggests the following several conclusions:

– the mouth of the outflow from Jamno was obstructed on 83 days in 1964 and 76 days in 1965, i.e. on an average of 22% of days in a year,
– in 1964, water inflow from the sea to the lake occurred on a total of 48 days, and in 1965 21% of all inflows occurred in November,
– in the years 1964-1965, 60% of inflows constituted one-day intrusions. Combined with two-day intrusions, they accounted for 84% of all cases; the maximum recorded duration of inflow from the Baltic Sea to Jamno was 11 days (from 7 November to 27 November 1964),
– the effect of marine waters on the lake waters was characterised by certain seasonality. It was the strongest in autumn and spring (i.e. in the period of storms, from November to February), the weakest in summer, and most variable in winter,
– the analysis of mutual contacts of marine and lake waters showed the existence of the following situations: during intensive marine water damming at the southern coasts of the Baltic Sea, immediate response of an increase in the water stages in Jamno occurred (in the case of unobstructed flow). The response was delayed in the case of obstructed flow, i.e. partial obstruction. Lack of the effect of the sea on waster stages in the lake was observed in the case of complete obstruction of Nurt Jamneński,
– flows in both directions occurring in Nurt Jamneński were largely variable in terms of discharge volume, reaching even several tens of $m^3 \cdot s^{-1}$,
– in the past (before the construction of the gate), the channel profile showed high variability, and in the case of high differences in water stages between the sea and lake, flow speeds in Nurt exceeded even 1 $m \cdot s^{-1}$,
– when water stages were similar, water in Nurt Jamneński stagnated, or its flow was negligible.

On the one hand, the above examples show the scale of mutual relations between two very different water masses. On the other hand, they show the most probable terms of their occurrence.

Daily surface water temperature fluctuations were observed on the background of air temperature fluctuations (Fig. 6) and water level fluctuations in the Baltic Sea (Fig. 7). Surface water temperature fluctuations were obviously characterised by higher stability. In more than 90% of the analysed cases, daily surface water temperature fluctuations were lower than 1°C, and in the case of air, such a situation was observed for 40% of the analysed data.

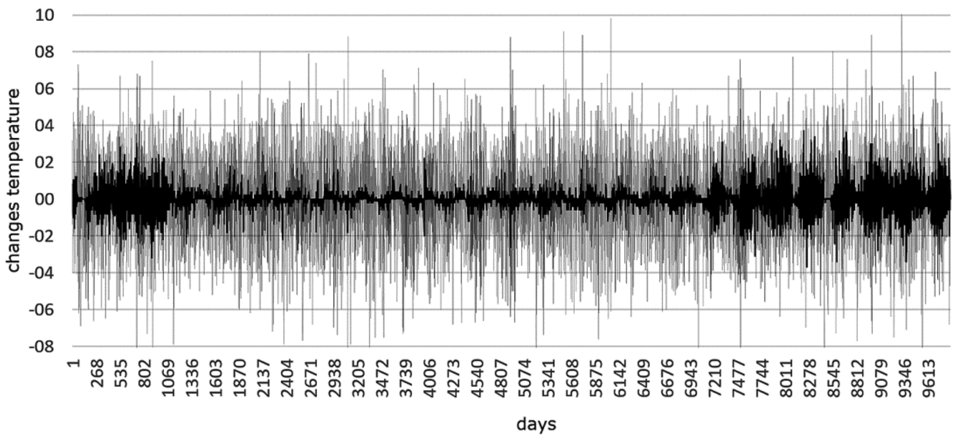


Fig. 6. Daily surface water temperature fluctuations (Jamno) and air temperature fluctuations (Koszalin) in the years 1987-2013

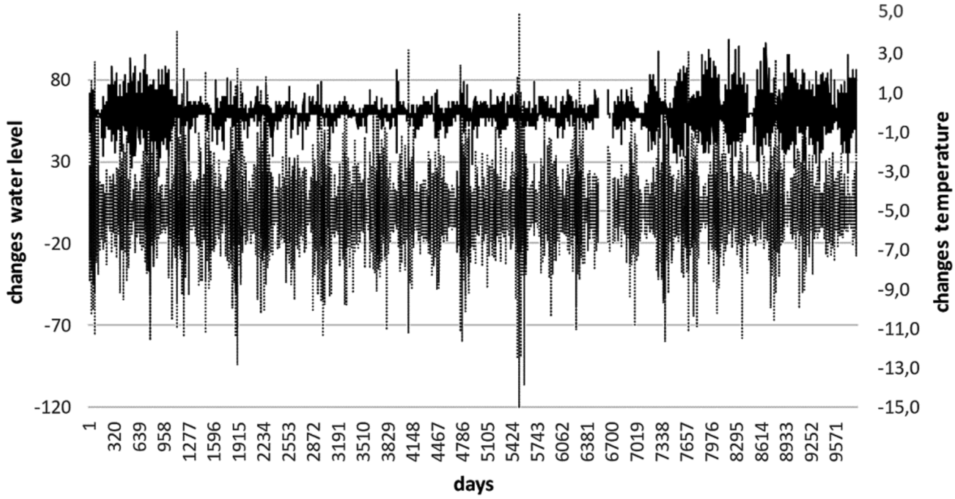
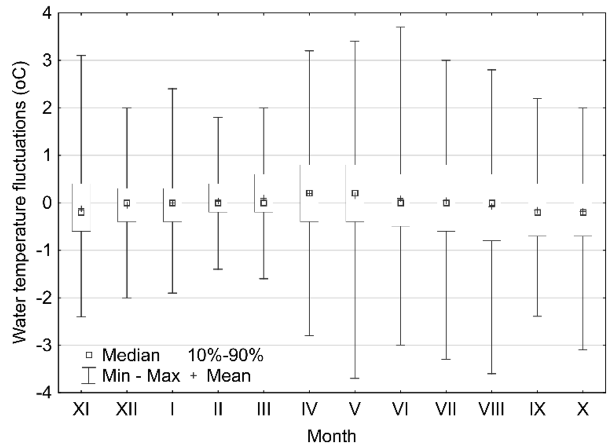


Fig. 7. Daily water temperature fluctuations (Jamno) and water level fluctuations in the Baltic Sea (Kołobrzeg) in the years 1987-2013

Ranges of daily water and air temperature fluctuations in reference to particular months are presented in Fig. 8a. Absolute maximum daily surface water temperature fluctuations reached up to 3.70°C, and in the case of air temperatures more than 11°C. The lowest daily surface water temperature fluctuations occurred in February and March (maximum up to 2°C), and the highest from April to August (maximum from 3 to 3.70°C). In the case of air temperatures, the highest daily fluctuations occurred in April and May, and the lowest in September (Fig. 8b). The trend analysis showed that in the years 1987-2013, an increasing tendency of daily surface water temperature fluctuations occurred (significant at a level of 0.1). The analysis showed that the greatest fluctuations occurred after 2004. In the monthly cycle, an increase in daily surface water temperature variability was observed in November, March, June, July, August, and September. The most obvious changes occurred in June and July (averaging 0.20°C·decade^{-1}). The analysis of daily air temperatures showed no significant changes in the years 1987-2013, either in the annual or monthly cycle.



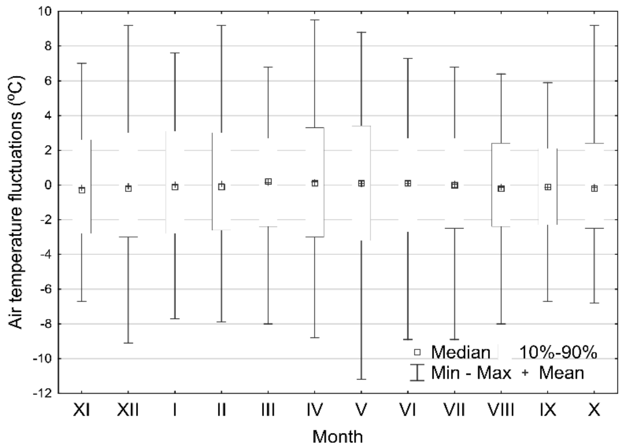


Fig. 8. Daily water temperature fluctuations and air temperature fluctuations in the monthly cycle

In the case of daily surface water temperature fluctuations and air temperature fluctuations, a weak mutual correlation occurs. As pointed out above, it is an expected result due to higher thermal stability of water. The highest value of the correlation coefficient was obtained for the variant with lack of a time step in air temperature fluctuations towards surface water temperature fluctuations (correlation coefficient r = 0.20). In the case of application of a time step from 1 to 10 days, the correlation coefficient adopted even lower values from -0.06 to 0.03. No correlation was also observed between daily water temperature fluctuations and daily water level fluctuations in the Baltic Sea.

The study results referring to long-term water temperature fluctuations in Jamno are in accordance with the majority of similar studies conducted in different regions of the world. In the case of Lake Tegel (Germany), in the years 1980-2007, Gross-

Wittke et al. (2013) recorded an increase in temperature by 0.90°C·dec^{-1}. In the meridional part of Central Europe, Dokulil et al. (2010) determined that an increase in temperature for 16 lakes located North of the Alps in the years 1940-2000 was the highest in spring and summer and equalled 0.25°C·dec^{-1}. Nõges and Nõges (2014) describing temperature fluctuations in two lakes in Estonia also determined the highest increase in water temperature in those seasons. In the case of Lake Peipsi, it reached a value in April of 0.48°C·dec^{-1} over the last half a century. Similar observations were confirmed by Pernaravičiute (2004) analysing thermal conditions in seven lakes in Lithuania (the highest increase in temperature in April and August was 0.8°C·dec^{-1}). Moreover, as a result of comparison of two decades in the years 1980-1990 and 1990 and 2000, he determined that higher water temperatures occurred in the second one. The analysis of water temperature fluctuations in Latvian lakes also showed positive tendencies (Apsite et al. 2014). In the case of Lake Ladoga, Naumenko et al. (2006) determined that mean increase in surface water temperature equalled 0.5-0.7°C·dec^{-1}. In the case of Baikal, an increase in temperature at a level of 0.2°C·dec^{-1} was observed over more than half a century (Hampton et al. 2008). In the case of Lake Chivero, an increasing trend of mean annual and mean maximum water temperatures was determined by Magadza (2018). Increasing trends of water temperature in European lakes over the last 35 years were determined by Lieberherr and Wunderle (2018). Schneider and Hook (2010) analysing trends in water temperature fluctuations in lakes on the global scale determined its increase among others in the area of the Black Sea, in northern China and Mongolia, or the United States. In the case of other lakes in Poland, an evident increase in water temperature in lakes is also observed (Dąbrowski et al. 2004, Ptak et al. 2018b, Woolway et al. 2017).

The large majority of lakes of moderate latitudes is generally characterised by an increase in temperature of surface waters. The scale of the process in addition to the primary factor, in this case air temperature, depends on local factors and individual parameters of the lake itself. It is important information in the context of hydrotechnical development that since 2013 changed the current functioning of Lake Jamno. From the perspective of the thermal regime of Lake Jamno, it is currently difficult to predict the consequences of the construction of hydrotechnical infrastructure on the canal connecting the lake with the sea. As emphasised by Ptak et al. (2018b), water temperature is determined by a number of factors (including among others the rate of water exchange or its transparency). Therefore, close interactions between particular components can have both a direct and indirect effect on the transformation of each of them – including temperature constituting an elementary parameter of water.

CONCLUSIONS

The paper presents detailed characteristics of surface water temperature in Lake Jamno. It was evidenced that over the period of the last forty years, a transformation of the thermal regime has occurred, resulting in dynamic heating of water. Such a situation is in accordance with the majority of cases both in Poland and around the world referring to the analysis of the issue of water temperature in lakes. Based on daily fluctuations, water temperature was characterised by high stability, reaching the strongest correlations with air temperature fluctuations with no time step. The period analysed in the paper concerns the functioning of Lake Jamno of natural (quasi-natural) character. From 2013, the storm gate existing on Nurt Jamneński changed the current conditions, as shown in the literature cited in the paper. The paper constitutes a point of reference for future (covering several decades) comparative research on water temperature fluctuations and the related assessment of human impact interfering with the functioning of the ecosystem.

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CHARAKTERYSTYKA I ZMIANY TEMPERATURY WODY JEZIORA JAMNO

Streszczenie

W pracy dokonano analizy warunków termicznych przymorskiego jeziora Jamno. Długoterminowy (1971-2013) przebieg temperatury wody wskazuje, że podlegała ona znacznemu ociepleniu (0,28°C·dek-1). W układzie miesięcznym wzrost temperatury wody notowany jest we wszystkich przypadkach poza okresem zimy (grudzień, styczeń, luty). Najszybciej woda ogrzewała się w kwietniu (0,58°C·dek-1) oraz maju i wrześniu (0,46°C·dek-1). W podobnym tempie ogrzewała się średnia roczna temperatura powietrza (0,27°C·dek-1), lecz współczynnik

korelacji obu ośrodków wynosił 0,40, co sugeruje, że inne czynniki mogły wpływać na rozkład temperatury wody. Temperatura wody w Jamnie oraz poziom wody w Bałtyku najsilniejsze pozytywne związki przybierały w półroczu zimowym oraz ujemne w półroczu ciepłym. Od roku 2013 na kanale łączącym jezioro Jamno z Morzem Bałtyckim zostały uruchomione wrota przeciwsztormowe, które zmieniły wiele dotychczasowych procesów i zjawisk odbywających się w tym akwenie. Praca obejmuje swym zakresem naturalny (quasi-naturalny) okres funkcjonowania tego jeziora i stanowi punkt odniesienia dla przyszłych badań nad jego termiką uwzględniającą m.in. wpływ antropopresji w postaci zabudowy hydrotechnicznej.