Ice cover thickness formulas for selected flow-through lakes of the upper Łeba River (Kashubian Lakeland, northern Poland) and an overview of GIS methods, models for determining the thickness of ice cover on the selected examples

Jacek Barańczuk

Department of Limnology, University of Gdansk, Bażyńskiego 4, 80-309 Gdańsk, Poland, e-mail: bgiojb@univ.gda.pl

Abstract: The lakes selected for the analysis are situated in the Kashubian Lakeland which is a proper research area as there is a benchmark lake with a long data series within the region. This lake is located in the central part of the lakeland, in the upper Radunia water catchment area, while the lakes not being hydrometrically supervised constitute part of the upper Łeba water catchment area. The main objective of this study is to determine the relationship between ice cover thickness on the flow-through lake undergoing constant hydrometric supervision and some selected flow-through lakes not being monitored. The following lakes were selected for the study: Lake Raduńskie Górne (the benchmark lake) and four hydrometrically unmonitored lakes: Długie, Wielkie, Reskowskie and Łapalickie. The fieldwork research was done in the period of 2003–2008. Moreover, in order to evaluate the data calculated with the use of empirical formulas, additional fieldwork research was carried out in 2016. The analysis made it possible to develop formulas that allowed the thickness of the ice covering the selected flow-through lakes of the upper Łeba water catchment area to be assessed with decent accuracy.

Key words: flow-through lakes, ice, ice thickness, trend analysis, GIS methods

Introduction

The occurrence of ice cover during winter seasons is a common phenomenon in lakes located within a temperate climatic zone (Borowiak and Barańczuk 2004; Barańczuk and Borowiak 2005). Ice cover is the main parameter when analysing the ice regime of lakes (Marszelewski and Skowron 2009; Barańczuk 2015; Barańczuk et al. 2017).

In the literature regarding ice phenomena on lakes there are few publications on ice regimes in particular physico-geographical regions (Barańczuk and Marchlewicz 2003; Solarzski et al. 2011) in which the ice regime is also shaped by some other factors such as: morphometry of the lake basins, water cycle and chemical composition of the water.

The ice phenomena observed in the Kashubian Lakeland during the 21st century have not usually been part of any scientific debate (Barańczuk and Marchlewicz 2003; Borowiak and Barańczuk 2004; Barańczuk and Borowiak 2005; Maślanka and Barańczuk 2007), or

the issues addressed by researchers have been narrowed to only selected benchmark lakes (Trusewicz et al. 2009; Chojński et al. 2015; Wrzesiński et al. 2015; Barańczuk et al. 2017). Therefore, there is little information relating to ice regimes of the lakes situated in this region. The easiest way to collect as much data on ice phenomena in the Kashubian Lakeland as possible is to carry out regular field studies and then develop empirical formulas that allow the ice regimes in the analysed region to be studied indirectly.

So far, empirical formulas have not been used frequently to analyse ice regimes in the Kashubian Lakeland. Among the published studies there is one addressing the issue of relations between the benchmark lakes in the region (Barańczuk 2018). Another study concerns forecasting ice cover occurrence on endorheic lakes situated within the same water catchment area as the benchmark lakes (Barańczuk and Barańczuk 2018) – the endorheic lakes constitute a dominating element of the Kashubian Lakeland water system (Borowiak and Barańczuk 2005; Borowiak and Barańczuk 2006).

The satisfying results of the already-mentioned studies and analyses by Borowiak et al. (2011) and by Borowiak and Barańczuk (2006), which confirmed a strong correlation between hydrological parameters of lakes situated in three different water catchment areas, have encouraged the author to formulate another question: What are the ice regimes of flow-through lakes situated in the same region but within a different water catchment area (upper Łeba River), not under hydrometric supervision (upper Radunia River)? May a hydrometrically monitored lake be a benchmark lake for determining the ice regimes of the unmonitored flow-through lakes of the upper Łeba River?

Study area

Four flow-through lakes situated in northern Poland, in the Kashubian Lakeland and within the upper Łeba River catchment area were selected for fieldwork research (Fig. 1). When taking the physico-geograph-

ical regionalisation of the Kashubian Lakeland by Gacki and Szukalski (1979) the studied lakes (Długie, Łapalickie, Reskowskie and Wielkie) are situated within two submesoregions – Central Heights (Centralne Wysoczyzny) and Lakeside Hills (Wzgórza Nadjeziorne) (Barańczuk and Maślanka 2007a; Barańczuk and Maślanka 2007b; Borowiak 2007a; Borowiak 2007b). The benchmark lake is situated in northern Poland, in the Kashubian Lakeland within the upper Radunia water catchment area, which is adjacent to the water catchment area of the lakes selected for the analysis (Borowiak and Barańczuk 2005).

Lake Długie and its water catchment area is the river spring area of the River Łeba. The river springs approximately 1 kilometre to the south of its confluence with the lake. Lake Długie is the first lake in the river-lake system of the River Łeba (Barańczuk and Maślanka 2007a).

The analysed lakes have differentiated morphometric parameters (Table 1). They are large and medium

Table 1. Morphometric characteristics of the lakes under study

Lake	Surface area	Volume	Max. depth	Mean depth	Retention time
	[hm ²]	[dam ³]	[m]	[m]	[yr]
Raduńskie Górne	387.2	60158.7	43.0	15.5	2.03
Długie	49.7	2968	11.6	6.0	1.18
Łapalickie	155.1	15025	23.6	9.7	2.60
Reskowskie	53.8	2125	9.8	3.9	0.17
Wielkie	36.0	2610	17.5	7.3	0.57

Fig. 1. Location map of the study area

1 – Lake Raduńskie Górne, 2 – Lake Długie, 3 – Lake Wielkie, 4 – Lake Reskowskie, 5 – Lake Łapalickie. Broken lines mark drainage divides.

lakes (Lange 1993) covering an area from 36.0 (Lake Wielkie) to 387.2 ha (Lake Raduńskie Górne). When taking the volume under consideration, Lake Raduńskie Górne (60158.7 dam³) is the largest one (Borowiak and Barańczuk 2006) and Lake Reskowskie is the smallest, having 2125 dam³ (Barańczuk and Marchlewicz 2003). Similarly, Lake Raduńskie Górne is the deepest – 43.0 m and Lake Reskowskie is the shallowest – 9.8 m.

The annual rate of total horizontal water exchange in the selected lakes (retention time), calculated as the relation of the amount of outflowing water to the total water body volume, fluctuates from 0.38 to 5.8. This means that the average retention time varies from 62 days (Lake Reskowskie) to 949 days (Lake Łapalickie).

Research methods

The empirical formulas illustrating the ice regimes were based on data obtained during fieldwork research carried out in the period of 2003–2008. Ice cover thickness on the selected lakes within the upper Łeba River water catchment area was measured 17 times, 15 metres from the shore with an accuracy of 0.5 cm. The measurements were carried out in accordance with the recommendations issued by the Institute of Meteorology and Water Management (IMGW).

In order to develop proper empirical formulas, data for the benchmark lake were also included in the study. Data on ice cover thickness on Lake Raduńskie Górne

as well as data regarding air temperature were obtained from the Gdańsk University Limnological Station in Borucino. The data on ice cover thickness are collected daily starting from the day when the whole lake is covered with ice, and it is safe to enter the ice cover, to the day of ice melting (Barańczuk and Barańczuk 2018). The measurements are taken at a measurement point situated 100 metres from the station, in accordance with the IMGW recommendations. During the measurements neither the structure nor the type of the ice was determined. All the collected data were analysed with the use of the Statistica software. In order to evaluate the usability of the developed formulas they were also cross-checked with real data regarding ice cover thickness on the selected lakes, collected during the fieldwork research in winter 2016.

Results

In order to determine whether there is any connection between the ice cover thickness on Lake Raduńskie Górne and the ice cover thickness on the analysed lakes, diagrams for the analysed parameter were developed for all the unmonitored lakes as well as for the benchmark one. On the basis of the diagrams (Fig. 2) it was possible to confirm a strong connection between particular lakes of the upper Łeba River catchment area and the benchmark lake situated in the upper Radunia River catchment area.

Fig. 2. Relationship between the ice cover thickness (in cm) on the research lakes (A – Lake Długie, B – Lake Łapalickie, C – Lake Reskowskie, and D – Lake Wielkie) and the benchmark Lake Raduńskie Górne

Table 2. Ice cover thickness models for the flow-through lakes of the upper Łęba River catchment area constructed on the basis of the ice cover thickness measured on the benchmark Lake Raduńskie Górne (ICT_{RG})

Lake	Model	R ²
Długie	$ICT_{DI} = 0.9018 ICT_{RG} + 7.81$	0.896
Łapalickie	$ICT_{La} = 0.0144 ICT_{RG}^2 + 0.3976 ICT_{RG} + 9.22$	0.881
Reskowskie	$ICT_{Re} = 0.0254 ICT_{RG}^2 - 0.0925 ICT_{RG} + 16.08$	0.929
Wielkie	$ICT_{Wi} = 0.0162 ICT_{RG}^2 + 0.3743 ICT_{RG} + 10.35$	0.906

Abbreviations: ICT_{DI} – the ice cover thickness on Lake Długie, ICT_{La} – the ice cover thickness on Lake Łapalickie, ICT_{Re} – the ice cover thickness on Lake Reskowskie, ICT_{Wi} – the ice cover thickness on Lake Wielkie. Ice cover thickness is in centimetres.

The correlation coefficient (R) between the ice cover thickness on Lake Długie (ICT_{DI}), which is a spring lake for the Łęba River, and the ice cover thickness on Lake Raduńskie Górne (ICT_{RG}) equals 0.947. It confirms a strong relationship between those two water bodies and the fact that they have similar ice regimes (Fig. 2A). The model presented in Table 2 shows that at the time when ice begins to cover Lake Raduńskie Górne, the ice cover is already approximately 9 cm thick on Lake Długie. However, the data collected during the fieldwork show that the ice cover on Lake Długie may be 12 cm thick.

Another analysed lake, Lake Łapalickie (ICT_{La}) (Fig. 2B), is the largest of all the selected ones (Table 2). Although it is the largest of the selected water bodies within the upper Łęba River catchment area, its correlation with the benchmark lake is the weakest ($R = 0.939$) in comparison to the other analysed flow-through lakes. However, when taking the general value of the rate, it is still strong. According to the model (Table 2), the ice covering Lake Łapalickie is less than one centimetre thicker than the ice cover on Lake Długie while forming the ice cover on the benchmark lake. The data collected during the fieldwork show that the ice cover on Lake Łapalickie was 13 cm.

A strong correlation between the ice cover thickness on the benchmark lake (Fig. 2C) and Lake Reskowskie (ICT_{Re}) was also revealed. The correlation rate in this

case is the highest of all the analysed flow-through lakes and it equals 0.964. According to the model (Table 2), at the time when ice begins to cover Lake Raduńskie Górne, the ice cover is approximately 16 cm thick on Lake Reskowskie while the data collected during the fieldwork show that it was 18 cm.

The last selected lake is Lake Wielkie (ICT_{Wi}) (Fig. 2D, Table 2). In this case the correlation rate is not as high as that calculated for the previously mentioned lake, yet still very high ($R = 0.952$). The model shows that at the time when ice begins to cover Lake Raduńskie Górne, the ice cover is 10.7 cm thick on Lake Wielkie while the data collected during the fieldwork show that it was similar to the ice cover thickness on Lake Długie.

Discussion

Determining the thickness of ice covering lakes situated in the northern hemisphere is of high importance as they have an enormous impact on local climate and weather conditions. Moreover, ice cover may affect the local economy by hindering water energy production, cooling water inlets and by damaging shore infrastructure. It may also affect the water balance by distorting the process of mass and energy transfer (Jacobson 2015). Ice cover reduces the exchange of humidity between the atmosphere and water thanks to its insulating capacity (Ohata et al. 2017). That is why research on ice cover and its thickness on multiple water bodies is essential for a better comprehension of the local/regional winter climate (Ohata et al. 2017; Gebre et al. 2013).

In the literature there are numerous examples of lakes (MacDonald Lake, Douglas Lake, Great Bear Lake, Great Slave Lake) or whole regions (western Siberia, the Northwest Territories – Canada) where ice cover thickness has been estimated using satellites and computer software, e.g. RADARSAT-2 (Murfit et al. 2018), GPS-PRN 2 and 24 satellites (Jacobson 2015), Sentinel – 1A Sentinel – 1B with SNAP tools enabling the processing of SAR images (Pointner et al. 2018), Advanced Micro-

Table 3. Observed (OBS) and calculated on the basis of models listed in Table 2 (MRG) values of the ice cover thickness in selected days of winter season of 2016. Values are given in centimetres

Date	Lake			
	Długie	Łapalickie	Reskowskie	Wielkie
9 JAN 2016				
OBS	20.0	18.0	19.0	19.0
MRG	17.7	15.3	18.1	16.4
17 JAN 2016				
OBS	20.0	19.0	21.0	20.0
MRG	18.6	16.1	18.6	17.1
24 JAN 2016				
OBS	23.0	20.0	21.0	22.0
MRG	20.4	17.7	19.8	18.7

wave Scanning Radiometer – Earth Observing System (Kang et al. 2010) using Wideband autocorrelation radiometry (Mousavi et al. 2018) or with the use of models, e.g. MyLake (Gebre et al. 2013) – a model of lake dynamics, 1-D thermodynamic – a model based on an air and water temperature stream as well as on ice and snow density (Ohata et al. 2016). Xiao et al. (2018) presented an interesting method of monitoring ice on lakes with the use of common internet cameras.

However, climate models are usually inaccurate and video cameras show only the moment when ice cover forms and melts (Xiao et al. 2018). This is why the authors used a model based on real data which can be automatically implemented to the model and provide analysis for larger areas.

The correlation between ice cover thickness on the benchmark lake and the selected lakes varies from good to very good (Table 2). Calculated values of the determination coefficient (R^2) range from 0.881 to 0.929 ($p < 0.05$) and they are higher than those obtained by Kang et al. (2010), ranging from 0.52 to 0.97, who studied relationships between the sensitivity of brightness temperature (T_B) from the Advanced Microwave Scanning Radiometer-Earth Observing System and data on ice cover thickness provided by the thermodynamic lake ice model for Great Slave Lake and Great Bear Lake. The satisfying values of the determination coefficient confirmed the effectiveness of the analysis on the relationship between ice cover thickness formed on the benchmark lake, situated in the upper Radunia River catchment area (Borowiak and Barańczuk 2006; Barańczuk 2015), and each of the selected flow-through lakes of the upper Łeba River catchment area.

The analysis of data collected during the fieldwork in 2016 and those derived from the models presented in table 3 showed that none of the obtained values fail to properly reflect the real values of ice cover thickness formed on the selected water bodies. The calculated ice cover thickness was lower by 0.9 cm for Lake Reskowskie and by 3.3 cm for Lake Wielkie when compared with the fieldwork data. However, when expressed as a percentage the values differ by a maximum 20% (Lake Wielkie), which is in line with the results obtained by Barańczuk and Barańczuk (2018) – 21%. Moreover, Wang et al. (2010) obtained similar results (differences reaching approx. 20%) when using the thermodynamic model based on satellite data verified by fieldwork data. When analysing ice cover on lakes and seas, the data from the model constructed by Wang et al. (2010) differed by only 11% from the satellite measurements. Moreover, they stated that the simulated ice cover thickness is usually overstated when the ice is thin. This was also confirmed by Jacobson (2015). His research found that ice cover thickness determined on the basis

of satellite data was lower by 1.4 cm in comparison with the fieldwork measurements, yet the data were verified only once. On the other hand, Ohata et al. (2016) obtained slightly different results when doing research on Abashiri Lake situated on Hokkaido Island in Japan. In this case, once – on 17th January – the model data on ice cover thickness were lower by 4 cm than the real data obtained during the fieldwork (89% of the real ice cover thickness) while on 18th February they were higher by 3 cm – 107%.

The results obtained by using a model based on real data, as presented in this study, are acceptable since they do not differ significantly from the data obtained during the fieldwork research. Using this type of model allows us to determine the relationship between ice cover thickness and climate changes in large, usually sparsely inhabited, areas (Brown and Duguay 2011).

Conclusions

The study presented herein provides a positive answer to the questions asked in the introductory part of the paper. The analysis regarding the possibility of using models extrapolating from real data on the ice cover thickness on Lake Raduńskie Górne, situated within the upper Radunia River catchment area, to the four selected flow-through lakes situated in the upper Łeba River catchment area may be considered promising. The results obtained when using the model are not significantly imprecise when compared to the real data obtained during the fieldwork in 2016. Moreover, the indeterminate factors are also in line with the data obtained and elaborated in a previous study on endorheic lakes by the authors (Barańczuk and Barańczuk 2018).

References

- Barańczuk J., 2007, Jezioro Stężycie (Lake Stężycie), [in:] Borowiak D. (ed.), Atlas jezior Kaszubskiego Parku Krajobrazowego (Atlas of the Kashubian Landscape Park Lakes), Ser. Bad. Limnol. 4. Wydaw. KLUG, Gdańsk: 261–266 (in Polish, English summary).
- Barańczuk J., 2015, Przebieg zjawisk lodowych na wybranych jeziorach Pojezierza Kaszubskiego (The course of ice phenomena on the selected lakes of the Kashubian Lakeland) [Dissertation], Department of Limnology of Gdańsk University, Gdańsk, 231 pp (in Polish).
- Barańczuk J., 2018, The statistical relation/coherence between ice regimes of Lake Raduńskie Górne and Lake Ostrzyckie, *Limnol. Rev.* 18(3): 103–108.
- Barańczuk J., Bajkiewicz-Grabowska E., Barańczuk K., Staszek W., 2017, The ice regime of Lake Raduńskie Górne (Kashubian Lakeland, northern Poland), *Limnol. Rev.* 17(2): 61–70.

- Barańczuk J., Barańczuk K., 2018, Models for calculating ice cover thickness on selected endorheic lakes of the upper Radunia (Kashubian Lakeland, northern Poland), *Limnol. Rev.* 18(4): 129–135.
- Barańczuk J., Borowiak D., 2005, Zjawiska lodowe jezior (Ice phenomena in lakes), [in:] Lange W. (ed.), *Jeziora górnej Raduni i jej zlewnia w badaniach z udziałem Stacji Limnologicznej w Borucinie* (Lakes of the upper Radunia River and its catchment in research with the participation of the Limnological Station in Borucino), Ser. Bad. Limnol. 3, Wydaw. KLUG, Gdańsk: 251–260 (in Polish, English summary).
- Barańczuk J., Marchlewicz R., 2003, Diversity of development of ice phenomena in chosen lakes of Kaszubskie Lakeland in winter 2003, *Limnol. Rev.* 3: 25–30.
- Barańczuk J., Maślanka W., 2007a, Jezioro Długie (Lake Długie), [in:] Borowiak D. (ed.), *Atlas jezior Kaszubskiego Parku Krajobrazowego* (Atlas of the Kashubian Landscape Park Lakes), Ser. Bad. Limnol. 4, Wydaw. KLUG, Gdańsk: 99–105 (in Polish, English summary).
- Barańczuk J., Maślanka W., 2007b, Jezioro Łapalickie (Lake Łapalickie), [in:] Borowiak D. (ed.), *Atlas jezior Kaszubskiego Parku Krajobrazowego* (Atlas of the Kashubian Landscape Park Lakes), Ser. Bad. Limnol. 4, Wydaw. KLUG, Gdańsk: 113–119 (in Polish, English summary).
- Borowiak D., Barańczuk J., 2004, Secular fluctuations of ice phenomena in Upper Radunia Lake, Kashubian Lakeland, *Limnol. Rev.* 4: 17–24.
- Borowiak D., Barańczuk J., 2005, Funkcje hydrologiczne jezior (Hydrological functions of lakes), [in:] Lange W. (ed.), *Jeziora górnej Raduni i jej zlewnia w badaniach z udziałem Stacji Limnologicznej w Borucinie* (Lakes of the upper Radunia River and its catchment in research with the participation of the Limnological Station in Borucino), Ser. Bad. Limnol. 3, Wydaw. KLUG, Gdańsk: 215–231 (in Polish, English summary).
- Borowiak D., Barańczuk J., 2006, Diversity of surface outflow from lakes which perform different hydrological functions, *Limnol. Rev.* 6: 13–20.
- Borowiak D., Barańczuk J., Marchlewicz R., 2003, Role of lakes without outflow in shaping conditions of water circulation in the catchment, *Limnol. Rev.* 3: 25–30.
- Borowiak D., Nowiński K., Barańczuk J., Marszelewski W., Skowron R., Solarczyk A., 2011, Relationship between areal hypolimnetic oxygen depletion rate and the trophic state of five lakes in northern Poland, *Limnol. Rev.* 11, 4: 135–142.
- Borowiak M., 2007a, Jezioro Reskowskie (Lake Reskowskie), [in:] Borowiak D. (ed.), *Atlas jezior Kaszubskiego Parku Krajobrazowego* (Atlas of the Kashubian Landscape Park Lakes), Ser. Bad. Limnol. 4, Wydaw. KLUG, Gdańsk: 133–139 (in Polish, English summary).
- Borowiak M., 2007b, Jezioro Wielkie (Lake Wielkie), [in:] Borowiak D. (ed.), *Atlas jezior Kaszubskiego Parku Krajobrazowego* (Atlas of the Kashubian Landscape Park Lakes), Ser. Bad. Limnol. 4, Wydaw. KLUG, Gdańsk: 149–154 (in Polish, English summary).
- Brown L.C., Duguay C.R., 2011, A comparison of simulated and measured lake ice thickness using a Shallow Water Ice Profiler, *Hydrol. Process.* 25(19):2932–2941.
- Choiński A., Ptak M., Skowron R., Strzelczak A., 2015, Changes in ice on polish lakes from 1961 to 2010 related to location and morphometry, *Limnologica* 53: 42–49.
- Gacki T., Szukalski J., 1979, Zróżnicowanie geoeekologiczne i regionalne oraz problemy antropizacji i ochrony środowiska geograficznego (Geoeological and regional differentiation, also problems of the anthropization and protection of the Cashubian Lake District geographical environment), [in:] Augustowski B. (ed.) *Pojezierze Kaszubskie* (Cashubian Lake District), Wydaw. GTN, Gdańsk: 221–253 (in polish, English summary).
- Gebre S., Boissy T., Alfredsen K., 2014, Sensitivity of lake ice regimes to climate change in the Nordic region, *Cryosphere* 8: 1589–1605.
- Jacobson M.D., 2015, Potential for estimating the thickness of freshwater lake ice by GPS interferometric reflectometry, *J. Geogr. Geol.* 7(1): 10–19.
- Kang K.-K., Duguay C.R., Howell E.L., Derksen C.P., Kelly E.J., 2010, Sensivity of AMSR-E brightness temperatures to the seasonal evolution of lake ice thickness, *IEEE Geosci. Rem. Sens. Lett.* 7, 4: 751–755.
- Lange W. (ed.), 1993, *Metody badań fizycznolimnologicznych* (Methods of physicolimnological studies), Wydaw. UG, Gdańsk, 175 pp (in Polish).
- Marszelewski W., Skowron R., 2009, Extreme ice phenomena on the lakes of Northern Poland, *Limnol. Rev.* 9(2–3): 81–89.
- Maślanka W., Barańczuk J., 2007, Termika i dynamika wód (Thermicity and dynamics of water), [in:] Borowiak D. (ed.), *Jeziora Kaszubskiego Parku Krajobrazowego* (Lakes of the Kashubian Landscape Park), Ser. Bad. Limnol. 5, Wydaw. KLUG, Gdańsk: 67–86 (in Polish, English summary).
- Mousavi S., De Roo R., Sarabandi K., England A.W., 2018, Effect of thin dry snow layer on the lake ice thickness measurement using wideband autocorrelation radiometry, *Proc. of the 2018 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2018)*, 22–27 July, Valencia: 7109–7112.
- Murfitt J.C., Brown L.C., Howell S.E.L., 2018, Estimating lake ice thickness in Central Ontario, *PLOS ONE* 13(12): 1–20.
- Ohata Y., Toyota T., Fraser A. D., 2017, The role of snow in the thickening processes of lake ice at Lake Abashiri, Hokkaido, Japan, *Tellus A* 69(1): 1–19.
- Ohata Y., Toyota T., Shiraiwa T., 2016, Lake ice formation processes and thickness evolution at Lake Abashiri, Hokkaido, Japan, *J. Glaciol.* 62(233): 563–578.
- Pointner G., Bartsch A., Forbes B. C., Kumpula T., 2018, The role of lake size and local phenomena for monitoring ground – fast lake ice, *Int. J. Remote Sens.* 40(3): 832–858.

- Skowron R., 2011, Zróżnicowanie i zmienność wybranych elementów reżimu termicznego wody w jeziorach na Niżu Polskim (Diversity and variability of selected elements of the thermal regime of water in lakes in the Polish Lowlands), Wydaw. Nauk. UMK, Toruń, 345 pp (in Polish, English summary).
- Solarski M., Pradela A., Rzętała M., 2011, Natural and anthropogenic influences on ice formation on various water bodies of the Silesian Upland (southern Poland), *Limnol. Rev.* 11(1): 33–44.
- Trusewicz Z., Markowski M., Barańczuk J., 2009, The influence of the North Atlantic Oscillation on variability of surface temperature of Lake Raduńskie Górne, *Limnol. Rev.* 9(2–3): 55–62.
- Wang X., Key J. R., Liu Y., 2010, A thermodynamic model for estimating sea and lake ice thickness with optical satellite data, *J. Geophys. Res.* 115(C12035): 1–14.
- Wrzesiński D., Choiński A., Ptak A., Skowron R., 2015, Effect of the North Atlantic Oscillation on the pattern of lake ice phenology in Poland, *Acta Geophys.* 63(6): 1664–1684.
- Xiao M., Rothermel M., Tom M., Galliani S., Baltsavias E., Schindler K., 2018, Lake ice monitoring with webcams, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.* IV-2: 311–315.