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# Variability and course of occurrence of ice cover on selected lakes of the Gnieźnieńskie Lakeland (Central Poland) in the period 1976–2015

*Bogumił* Nowak[1,*], *Dominik* Nowak[1], and *Mariusz* Ptak[2]

[1]Institute of Meteorology and Water Managament – National Research Institute, Podleśna 61, 01-673 Warszawa, Poland
[2]Department of Hydrology and Water Management, Adam Mickiewicz University, B. Krygowskiego 10, 61-680 Poznań, Poland

**Abstract**. The paper presents the analysis of the course of ice phenomena on four lakes (Lednica, Żnińskie Duże, Biskupińskie, Powidzkie) in central Poland in the period 1976–2015. The obtained results show changes in their ice regime that occurred over the last 40 years. An advance of the term of decline of ice cover was determined (by 2.5 day·dec$^{-1}$on average for all lakes), as well as a reduction of duration of ice cover (by 4.4 day·dec$^{-1}$ on average for all lakes), and a decrease in its maximum thickness (by 2 cm·dec$^{-1}$ on average for all lakes). Such a situation should be associated with the observed warming, as confirmed by the course of air temperature for station Gniezno, where in the period of the winter half-year (November-April), an increase in temperature was recorded by 0.37°C·dec$^{-1}$.

## 1 Introduction

The functioning of lake ecosystems depends on many factors, and particularly atmospheric and hydrological processes. A characteristic feature of lakes of the moderate zone is the occurrence of ice phenomena in the winter half-year, defined as the presence of ice in water in any form (shore ice, ice cover). Compact ice cover is of the highest importance. It constitutes an isolator for water masses against external factors [1]. It eliminates the effect of wind generating wave action and currents, limits insolation, etc. The presence or absence of ice in a given season, or duration of ice cover are of high importance for processes occurring not only in winter, but also in the further part of the year. This refers to both biotic and abiotic conditions. Adrian et al. [2], analysing changes in plankton in spring depending on the duration of ice cover, evidenced that it affected the time and magnitude of the peak abundance of selected species. Haberman and Haldna [3], analysing the variability of zooplankton in polymictic Lake Võrtsjärv (Estonia), determined that it was dependent on water temperature (more in spring than in autumn), and water temperature depended among others on the occurrence of ice. Nguyen et al. [4] found that ice cover considerably suppresses water movement in the Saginaw Bay (Lake Huron), almost leading to stagnation in February. This is of high importance among others for the occurring dissolved substances, and for their

* Corresponding author: rugosa@op.pl

further release in more extensive water circulation in the lake. Austin and Colman [5] recorded a decrease in the duration of ice cover in Lake Superior, resulting in earlier development of thermal stratification. As evidenced by the above examples, the response of lakes to changes in ice conditions is rapid and evident. Li et al. [6] evidenced that when ice thickness showed a decreasing tendency, changes in the concentration of nutrients occurred in shallow Lake Ulansuhai (China) in the winter season. Considering the observed climate warming, further changes can be expected in the ice regime of lakes [7, 8], and as a consequence a transformation of entire lake ecosystems. Moreover, it should be emphasised that the manifestation of climatic signals affecting the ice regime can be obscured by local conditions of lakes [9]. In the case of Poland, obtaining possibly extensive information regarding the course of hydrological processes is particularly important in reference to its central part, characterised by the scarcest water resources. A complex approach to the hydrosphere is of key importance for undertaking potential measures aimed at among others an increase in water retention, with lakes as its main component.

The objective of the paper is the determination of long-term changes in the ice regime of selected lakes in the Wielkopolsko-Kujawskie Lakeland (Fig. 1), and evaluation of the effect of climatic factors and morphometric parameters of lakes on the development and occurrence of ice phenomena on the lakes.

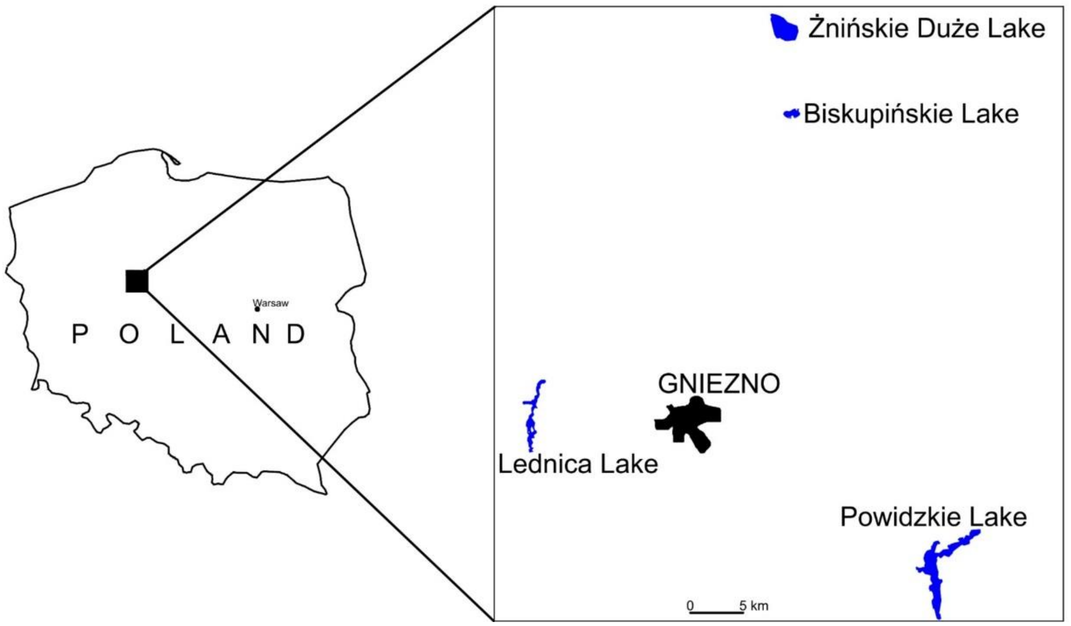


**Fig. 1.** Location of study objects.

## 2 Materials and methods

The paper is based on data concerning ice phenomena on four lakes (Tab. 1) from central Poland covering the years 1976–2015. The data were obtained from the collections of the Institute of Meteorology and Water Management – National Research Institute, and cover: the term of the beginning and end of ice cover, its duration, and maximum thickness. The analysis of trends in changes in ice conditions of the discussed lakes and air temperature in the analysed period was conducted by means of linear regression in Microsoft Excel software, with adopted significance level of p=0.05. The used climatic data concerning mean annual and mean monthly air temperatures, were obtained from station Gniezno located in the central part of the discussed area.

**Table 1.** Morphometric data of the studied lakes (before: [10]).

| No. | Lake | Area [ha] | Volume [thous.m$^3$] | Depth [m] | |
|---|---|---|---|---|---|
| | | | | average | max |
| 1 | Lednica | 325.0 | 24397.0 | 7.0 | 15.1 |
| 2 | Żnińskie Duże | 420.5 | 29492.6 | 6.8 | 11.4 |
| 3 | Biskupińskie | 107.0 | 6397.2 | 5.5 | 13.7 |
| 4 | Powidzkie | 1097.5 | 134776.2 | 11.5 | 46.0 |

# 3 Results and discussion

Features of the ice regime of the analysed lakes are presented in Table 2, and their course in Fig 2–4.

**Table 2.** Parameters ice cover lakes for the years 1976–2015.

| Parameters \ Lake | Lednica | Duże Żnińskie | Biskupińskie | Powidzkie |
|---|---|---|---|---|
| Earliest date of appearance of ice cover | 25-Nov | 28-Nov | 17-Nov | 10-Dec |
| Average date of appearance of ice cover | 25-Dec | 31-Dec | 20-Dec | 12-Jan |
| Latest data of appearance of ice cover | 08-Feb | 07-Feb | 23-Feb | 25-Feb |
| Earliest date of disappearance of ice cover | 15-Jan | 02-Jan | 31-Dec | 16-Jan |
| Average date of disappearance of ice cover | 08-Mar | 06-Mar | 07-Mar | 11-Mar |
| Latest data of disappearance of ice cover | 14-Apr | 13-Apr | 09-Apr | 13-Apr |
| Average duration of ice cover [days·year$^{-1}$] | 60.0 | 53.7 | 63.1 | 43.8 |
| Maximum thickness of ice cover [cm] | 50.0 | 55.0 | 51.0 | 50.0 |

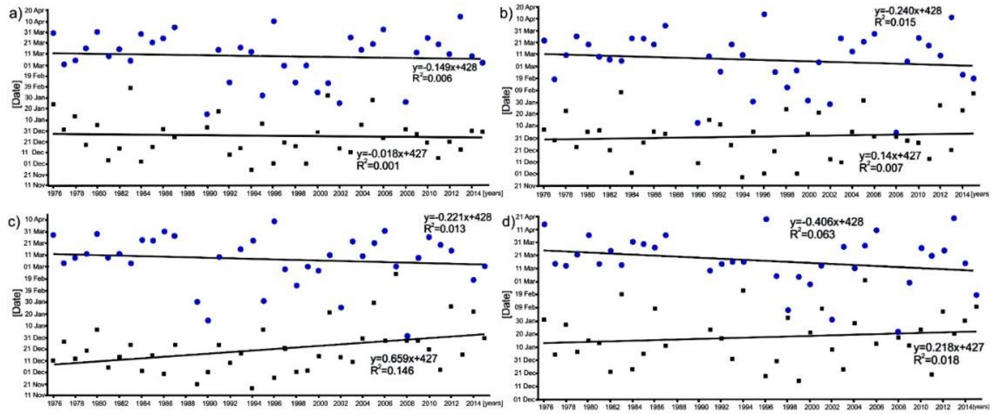


**Fig. 2.** Terms of the beginning (squares) and end of ice cover (dots), a) Lednica Lake, b) Żnińskie Duże Lake, c) Biskupińskie Lake, d) Powidzkie Lake.

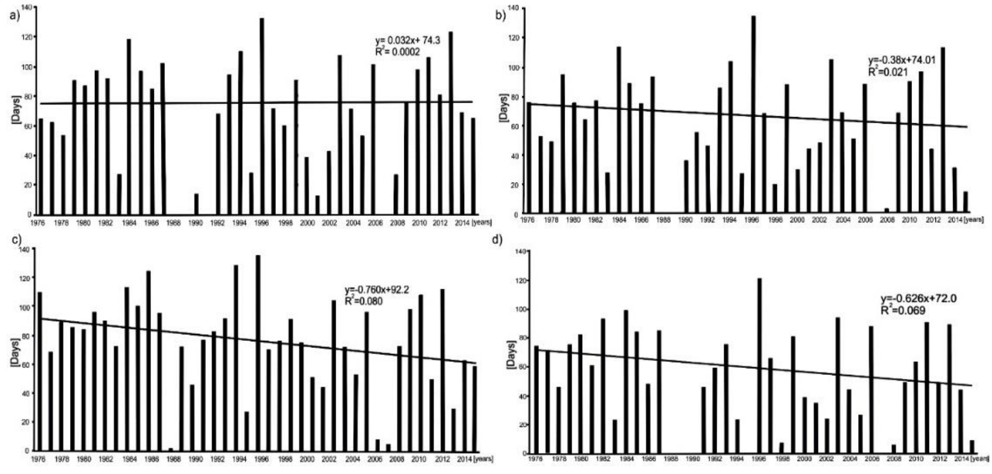


**Fig. 3.** Duration of ice cover, a) Lednica Lake, b) Żnińskie Duże Lake, c) Biskupińskie Lake, d) Powidzkie Lake.

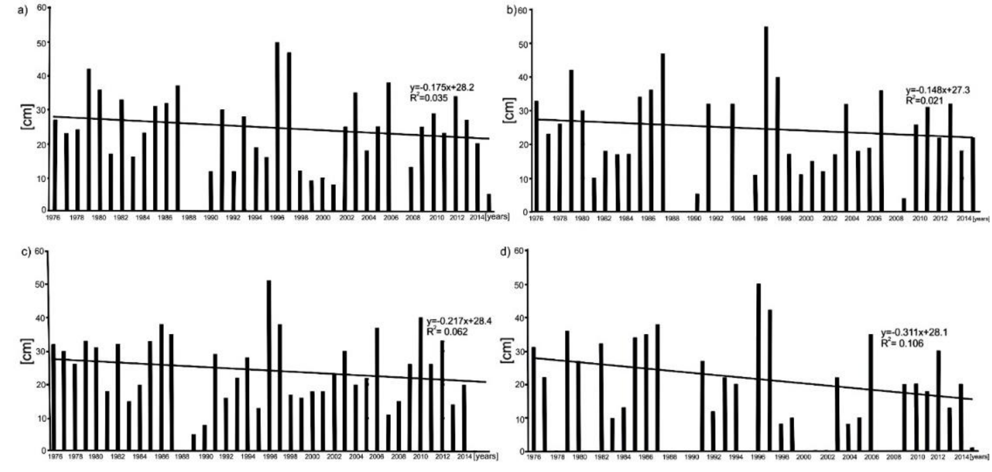


**Fig. 4.** Maximum thickness of ice cover.

As presented in Table 2, in spite of a small distance between particular lakes, individual parameters concerning ice conditions were variable, whereas higher variability was recorded for dates of appearance of ice cover. Ice cover usually developed on the discussed lakes after 20 December. Only on Lake Powidzkie it appeared after 10 January. On Lake Biskupińskie, ice cover appeared on average 22 days earlier than on Lake Powidzkie. Such a situation probably results from the morphometric parameters of the lakes. The former has the smallest volume of the lake basin, and the latter the largest (Tab. 1). This translates into the lowest and greatest heat resources accumulated in the lakes. Even higher variability concerns dates of appearance of ice cover in particular years of the studied 40-year period. It appeared the earliest already on 17 November, and the latest on 25 February (Tab. 2).

In the case of dates of disappearance of ice cover, they were approximate and usually occurred around 10 March, whereas on average ice cover was disintegrated the earliest on Lake Żnińskie Duże, and the latest on Lake Powidzkie (Tab. 2). Differences in the latter case amount to only several days and result from the impact of atmospheric factors. Atmospheric conditions (air temperature, insolation, wind) show low variability in all cases. They are key factors in the process of disintegration of ice cover.

Different time of development and disappearance of ice cover within particular lakes translated into its different durations. Dates of appearance and disappearance of ice cover determined its duration, although they cannot be directly associated, because between the first appearance of a given ice phenomenon and the last day on which it was recorded, days without the phenomenon could occur. Such a situation has been increasingly frequently observed over the recent years, as reflected in the number of days with solid ice cover (Fig. 3). For the analysed lakes, the values differed by 19 days on average, whereas ice cover usually persisted the longest on Lake Biskupińskie, and the shortest on Lake Powidzkie (Fig. 3, Tab. 2).

Similarly as in the case of the parameter analysed above, substantial differences between particular years are also observed in the case of thickness of ice cover. The parameter varied from 0 to 55 cm over the analysed 40-year period, whereas an evident dependency on the recorded air temperature was observed. Lower variability occurred in the case of maximum thickness of ice cover in particular lakes. In all lakes, it was approximate in consecutive years (Fig.4). This suggests that it depends less on morphometric parameters on lakes, and primarily on the regional climatic factor.

The analysis of the data suggests the predominance of the tendency for a reduction of the ice season on lakes in central Poland, as determined in three out of four cases. The term of the beginning of development of ice cover in the case of Lake Lednica showed no tendency, and in the remaining cases it occurred increasingly later (from 1.4 $day \cdot dec^{-1}$ to 6.5 $day \cdot dec^{-1}$). In the case of disappearance of ice cover, an acceleration of the phenomenon was recorded – on average from 1.4 $day \cdot dec^{-1}$ to 4 $day \cdot dec^{-1}$ (Fig. 2) This affected the duration of ice cover, reduced by a maximum of more than one week (Fig. 3). Ice cover also became thinner. In the case of maximum annual values, a decrease in ice thickness varied on average from 1.7 to 3.1 $cm \cdot dec^{-1}$ (Fig. 4).

The results described in the paper correspond with the current research trend concerning changes in the course of ice phenomena on lakes. A reduction of the duration of the ice season generally occurs, although the scale of the process is variable and depends on the lake's location, its individual parameters, and local conditions. Changes in ice cover on Lake Superior over 150 years were evident: the beginning of development of ice cover occurred later by an average of 1.6 $day \cdot dec^{-1}$, and its end earlier by an average of 1.7 $day \cdot dec^{-1}$ [11]. In the case of Lake Lunz (Austria), Kainz et al. [12] observed a reduction of duration of ice cover, and the average rate of the phenomenon amounted to 1.85 $day \cdot dec^{-1}$. In research on Lake Mendota (USA), Magee et al. [13] found that the development of ice cover occurred 9 days per century later, and its disintegration occurred 12.3 days per century earlier, resulting

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in a decrease in duration of ice cover (by 21.3 days per century). In research on 75 lakes on the Northern Hemisphere, Benson et al. [14] determined later freezing of lakes (0.3–1.6 day·dec$^{-1}$), earlier disappearance of ice (0.5-1.9 day·dec$^{-1}$), and its shorter duration (0.7–4.3 day·dec$^{-1}$). In the case of lakes in Poland, the issue concerning ice conditions on lakes is popular among researchers [15–18], and the results obtained in the paper correspond with earlier publications referring to long-term changes [19, 20]. Marszelewski and Skowron [21] treat changes in the course of ice phenomena on lakes in Poland as an indicator of climate warming. Changes concerning air temperature for station Gniezno (Fig. 5) were taken into account in this context. Mean temperature for the station amounted to 8.3°C, and in the period of the last 40 years it was subject to considerable increase – by 0.37°C·dec$^{-1}$ on average. Mean temperature in the winter half-year, when ice phenomena are observed on lakes, increased in a similar range (Nov-Apr, Fig. 5).

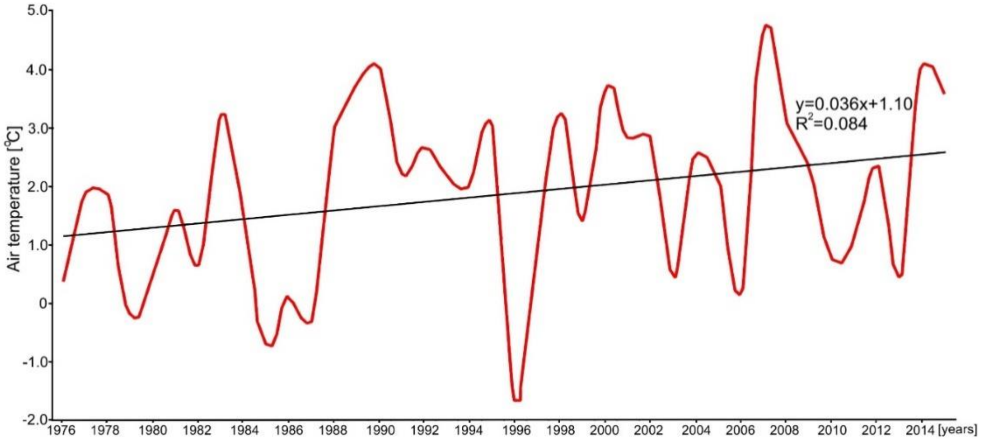


**Fig. 5.** Course and tendency of changes in mean air temperature in cold half-year for Gniezno (1976–2015).

In the monthly cycle, the highest temperature increase was determined for July (0.73°C·dec$^{-1}$) and April (0.73°C·dec$^{-1}$). Due to strong correlations of temperature of air and water [22], an increase in the former will contribute to an increase in the latter. As a consequence, heat resources accumulated in lakes increase [23]. Such a situation can lead to their longer release, and in the context of occurrence of ice cover – to its delayed development. In spring, an increase in air temperature will contribute to faster disappearance of ice cover. Such a situation was confirmed in all cases, where an advance of the term of disappearance of ice phenomena and ice cover was recorded with simultaneous substantial (one of highest in the annual scale) increase in air temperature in April.

In reference to lakes of the Northern Hemisphere, Dibike et al. [24] forecast a reduction of duration of ice cover by an average of 15 to 50 days. Such a situation will substantially change the current parameters of lakes. As signalled above, in the case of the study area, issues related to a change in the distribution of the components of the water balance will be of key importance. In this context, a reduction of duration of ice cover will cause among others longer contact of water with atmosphere, which will in turn contribute to an increase in evaporation from its surface. The situation will contribute to increasing water deficits observed in the area.

## 4 Conclusions

The analysis of the ice regime of four lakes in central Poland over the last four decades showed its transformations. Results obtained in the study are confirmed by current research on long-term variability of ice conditions on lakes both in Poland and all over the world. An earlier term of end of ice phenomena, and consequently their shorter duration are a result of the observed global climatic changes. In reference to the presented region, this is confirmed by the course of mean annual and mean monthly air temperatures. In the case of the latter, particularly substantial warming occurred in spring, i.e. in the period of disintegration of ice cover. The review of the literature cited in the paper suggests the conclusion that changes in the course of ice phenomena will considerably affect the functioning of all processes and phenomena occurring in lakes. In the case of the discussed area (considered as the most deficient in water in Poland), changes contributing to a decrease in the amount of water retained in the local lakes will be particularly unfavourable.

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