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Original article

The ice phenomena dynamics of small anthropogenic water bodies in the Silesian Upland, Poland

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ABSTRACT

The aim of this study was to determine the dynamics of the process of a course of ice creation phenomena in two small water bodies located in the Silesian Upland. The studies and observations of ice formation on the water bodies were conducted during the period 10th November 2011 to 23rd March 2012. The following parameters were determined each day: degree of ice coverage on each water body, thickness and ice structure and thickness of snow cover on each water body. From the studies it results that a course of the ice formation of both water bodies was almost identical. The same maximum ice thickness was recorded in both cases. It was 36 cm in that season, with slight differences in average thickness. The course of particular phases of ice formation in different water regions was also very similar. The number of days with the ice phenomena and the number of days from the beginning to the end of the ice phenomena were identical in both cases, being 96 and 131 days, respectively. The slight differences over several days were recorded in the case of: number of days with shore ice (lb), number of days with partial ice cover (lcz), number of days with an incomplete ice cover (lnp), number of breaks in the ice cover (B). Additionally, with daily measurements of ice cover thickness the relationships between the course of the average daily air temperature from the meteorological station of Faculty of Earth Sciences of University of Silesia and the daily changes in the ice thickness in the water regions in question were determined by using Spearman's correlation coefficient. In both cases the relationships were strong and they were r= -0,84(p<0,001) for the Amendy water body and r= -0,87 (p<0,001) for the Żabie Doły S water body. The maximum and average ice thickness, duration of the ice phenomena and ice cover and the obtained correlation coefficients between the air temperature and the changes in the ice thickness show that the water bodies in question are characterized by a quasi-natural ice regime.

KEY WORDS: lake ice, water bodies, ice cover, limnology, Silesian Upland

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1. Introduction

The research on lakes and water bodies shows a great interest in the phenomena of ice. There have been more and more published articles recently dealing with the ice regime of water bodies and investigating this issue in the long-term (LIVINGSTONE, 1997, 1999, 2000, 2003; MAGNUSON ET AL., 2000; MARSZELEWSKI & SKOWRON, 2006; SKOWRON, 2009, 2011; CHOIŃSKI ET AL., 2015). This approach recognizes that they are one of the indicators of climate change taking place nowadays (MAGNUSON ET AL., 2000; POCIASK-KARTECZKA & CHOIŃSKI, 2012; BENSON ET AL., 2000; WEYHENMEYER ET AL., 2004; JENSEN ET AL., 2007; SHARMA ET AL., 2016). However, there are hardly any studies where the researchers made daily observations and measurements of the ice phenomena within one or two water regions (RZĘTAŁA & RZĘTAŁA, 2009, 2012; RZĘTAŁA & SOLARSKI, 2011; RZĘTAŁA, 2012, 2014; MACHOWSKI, 2013, 2014). These types of study are laborious and time-consuming and require regularity from the researchers. An effect of the daily measurements and observations of the ice phenomena is a set of detailed data about: ice cover thickness, dynamics of ice increment and ablation, its horizontal and vertical structure, influence of the snow layer on shaping the dynamics and course of the ice formation and relationships between changes in the atmospheric air temperature

and changes in the ice cover thickness. The daily measurements of the ice thickness measurements and the snow cover accumulated on it can be used for making thermodynamic models which have been used more and more frequently in limnology (LEPPÄRANTA, 1983; VAVRUS ET AL., 1996; STEFAN & FANG, 1997; FANG & STEFAN, 1998; GAO & STEFAN, 1999; MÉNARD ET AL., 2002; ELO, 2007; LEPPÄRANTA & WANG, 2008; YANG ET AL., 2012).

2. Aim and methods

The aim of the study was to determine the ice formation dynamics of two small water bodies located on the Katowice Upland, within the central part of the Silesian Upland. The investigations and observations were performed daily, from 10 November 2011, when first night-time ground frosts were recorded, until the total disappearance of the ice phenomena in the water bodies which occurred on 23 March 2012. In the beginning the ice thickness was measured using a millimeter caliper, and then by using a specially made measurement scythe, prior to drilling a hole using an ice grill. Every day the degree of ice cover on the water body, and its vertical structure and thickness of the snow layer on the ice were also determined. The data collected constituted the basis for determining the duration of particular phases of ice formation on the water bodies and they were identified on the basis of the degree of ice coverage of the water bodies (Tab. 1). There were: a number of days with shore ice (lb), a number of days with partial ice cover (lcz), a number of days with an incomplete ice cover (lnp), a number of days without ice from the beginning until the end of the ice phenomena (lbl), a number of days with complete ice cover (lp), a number of complete ice formations (lpz), a number of breaks in the ice cover (b), a number of days with the ice phenomena (lzl), a number of days of the ice phenomena from the beginning until the end (ld). On the basis of the daily ice thickness measurements its thickness was determined: an average for the entire duration of the ice phenomena, an average when there was complete ice cover and the maximum thickness. The maximum daily increment and loss of ice thickness was also determined. A comparison of the daily changes in the ice cover thickness and the average daily air temperature from the meteorological station of the Faculty of Earth Sciences of the University of Silesia in Sosnowiec and constituted the basis for calculating the correlation coefficients between both variables. In accordance with the Kolmogorov-Smirnov test it has been established that the variables in question did not show a normal distribution, which is why Spearman's rank correlation coefficient was used. The calculations were made using tatistica 10.0 software.

Table 1. The ice formation phases of both water bodies in the winter season of 2011/2012

No.	Name	lb	lcz	lnp	lbl	lp	lpz	b	lzl	ld
1	Amendy	7	7	11	35	71	5	7	96	131
2	Żabie Doły S	6	6	13	35	71	5	5	96	131

Legend: lb – a number of days with shore ice, lcz – a number o days with a partial ice cover, lnp – a number of days with an incomplete ice cover , lbl – a number of days without ice from the beginning to the end of the ice phenomena, lp – a number of days with a complete ice cover, lpz – a number of days of complete ice formations, b – a number of breaks in the ice formation, lzl – la number of days with the ice phenomena, ld – a number of days from the beginning to the end of the ice phenomena

3. Study area

Two small water bodies located on the municipal-industrial area were selected for the investigations. Both water bodies are in the central part of the Katowice conurbation, in the territory of Łagiewniki, in Bytom quarter. One of them was the Amendy water body formed as a result of flooding a small rock material working. Its area was 1.3 ha, and average depth 1.6 metrs (SOLARSKI ET AL., 2011; SOLARSKI, 2017). The water body stored 21.4 dam^3 water. The other one was the Żabie Doły S water body of which the basin was formed as a result of ground subsidence as a consequence of underground coal mining (MACHOWSKI, 2010; MACHOWSKI ET AL. 2016). It is located in the area of the Żabie Doły Nature and Landscape Complex, and during the tests its area was 2.6 ha, with an average depth of 1.7 m level and the amount of water retention being 43.3 dam^3. Since the maximum and average depths are low, both water bodies belong to polymictic (Tab. 2). The objects selected for the investigations are a distance of 2 km from each other (Fig. 1).

Table 2. Basic information on both water bodies

No.	Name	Coordinates	Altitude [m n.p.m.]	Area [ha]	H_{avg} [m]	H_{max} [m]	Tc [dam^3]	G	H	M
1	Amendy	50°19'36"N; 18°55'34"E	287.7	1.3	1.6	3.2	21.4	P_e	B	P
2	Żabie Doły S	50°19'45"N; 18°57'17"E	278.0	2.6	1.7	2.9	43.3	N	B	P

Havg – average depth; Hmax - maximum depth; Tc - Total capacity; G – Genesis: Pe – polygenetic, N - subsidence bowl, H – hydrological: B – outflow less water body type; M – Mixing type: P – polymictic

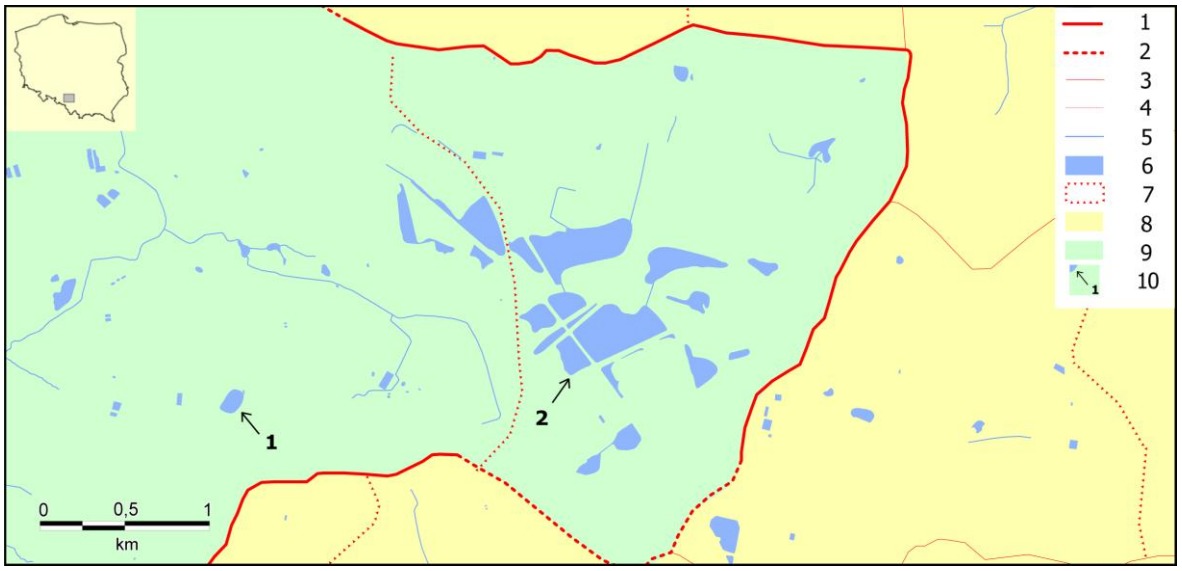

Fig. 1. The location of the water bodies within the hydrographical network
1 – first order drainage divides, 2 – first order drainage divides (uncertain), 3 – fourth order drainage divides, 4 – fourth order drainage divides (uncertain), 5 – watercourses, 6 – water bodies, 7 – non-drained areas, 8 – the Vistula River basin, 9 – the Oder River basin, 10 – the two water bodies – numbers like in the Tab. 1 and 2, 11 – towns

4. Results

In the winter season of 2011/2012 the atmospheric conditions favorable for forming the lake ice were already at the beginning of the second week of November. In the period from 11 to 30 November the average daily air temperature values oscillated around 0°C (Fig. 2). At night there were ground frosts, and during the day the temperature reached positive values. At that time Poland was under the influence of anti-cyclonic systems who's centres were formed over northern Europe. The anti-cyclones formed, among others, over Scandinavia, caused an inflow of cold air-masses from a northerly direction. Lightly overcast conditions, characteristic of anti-cyclonic systems, resulted in an increase in insolation during the day, and quick heat emission to the atmosphere at night.

The development of ice phenomena in both water bodies in question, observed on 13 November, was an effect of air temperature oscillation around 0ºC. Presence of an crystalline ice layer a few millimeters thick was recorded in the littoral zones of the water bodies on that day. In spite of maintaining an average temperature at a level of a few degrees above 0°C, in the second half of November, presence of partial, incomplete and complete ice cover was found on both water bodies (Fig. 2, Tab. 1). The ice formation phases of the water bodies were differentiated on the basis of the degree of their coverage with lake ice. Partial cover has a significant share in the water body area, although it does not exceed 50% of its area. Incomplete ice cover occupies over 50% of the water body area, it does not isolate it completely from the atmospheric conditions. Complete ice cover (100%) separates the limnic waters from the ground atmosphere layer (Tab. 1). During the days with ground frost the complete ice cover on the Amendy water body was maintained for 3 days, and on the Żabie Doły S water body it lasted for 4 days. On those days the dynamics of the ice thickness increment was insignificant, being below 0.1 cm per day during the first two weeks of the observations. In the last days of November there were a few days of warming (25–28.11.2011), resulting in disappearance of the ice phenomena from the water bodies in question, although at the turn of November into December was followed by cooling which resulted in re-occurrence of complete

ice cover on both water bodies. The surface waters of the water bodies in question were so cooled that they froze completely almost immediately (Fig. 2). The complete, and then partial, ice cover of which the maximum thickness did not exceed 0.5 cm persisted for a few subsequent days (Amendy – 4 days, Żabie Doły S - 3 days) (Fig. 2).

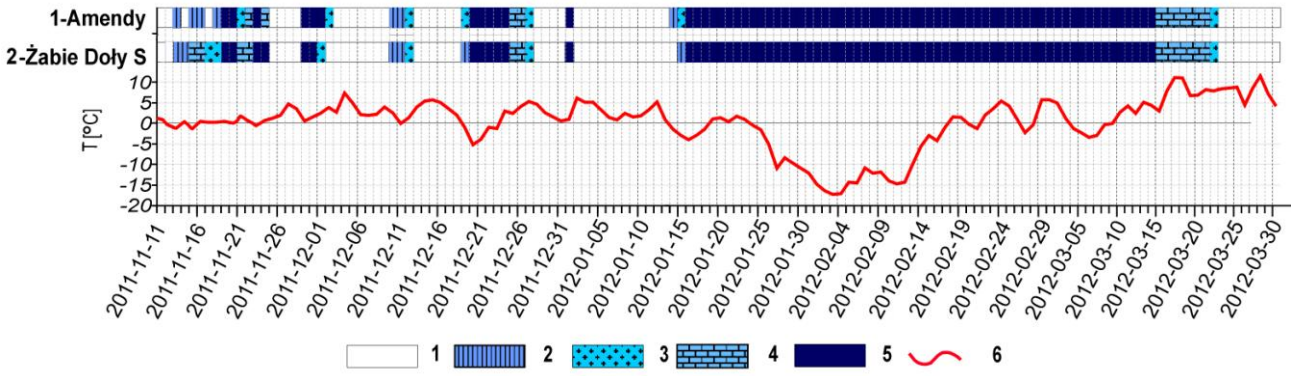

Fig. 2. The sequence of the particular phases of ice formation at the two water bodies in the winter season of 2011/2012
1 – no ice phenomena, 2 – shore ice, 3 – partial ice cover, 4 – incomplete ice cover, 5 – complete ice cover, 6 – average daily air temperature

From the first of December to the twelfth of January 2012 the air temperature oscillated around 0°C. This was the consequence of a change in the air circulation over Europe, and atmospheric fronts passing over Poland, and which brought an inflow of air masses from a westerly direction. Occurrence of the ice phenomena at that time was a result of occasional night-time ground frosts or an episodic inflow of arctic air (19.12.-23.12.2011) (Tab. 3). During such an episode the water bodies in question were covered completely with ice of a thickness which did not exceed a few centimeters (Fig. 2).

The first significant cooling took place during the first half of January (Figs. 2, 3, 4). The air temperature over Poland was formed initially by the polar-maritime air masses coming from a north-westerly direction. The water bodies which had cooled down from the beginning of the second week of November were quickly covered completely with ice. The ice formation process lasted one day in the case of the Żabie Doły water body, and two days in the case of the Amendy water body (Fig. 2). Freezing of the water bodies took place in conditions of snowfall which led to the formation of primary turbid ice of a random crystalline structure. Its maximum thickness was 1.6 cm and 2.0 cm, in the Amendy and Żabie Doły S water bodies, respectively (Figs. 3, 4).

The developing extensive stationary anti-cyclone from the centre over the lakes of Ladoga and Onega caused an inflow of frosty polar-continental air masses from a north-easterly direction. Such a baric system contributed to a big drop in air temperature during the period from 26 January to 14 February 2012 (Fig. 2). The deep cooling was accompanied by a slight snowfall which resulted in the formation of a one centimeter thick layer on the water body ice. A significant decrease in the temperature in that period caused a dynamic increment of the ice thickness in both water bodies. As a consequence of the cooling of the subsequent water layers the secondary crystalline ice, characterized by a vertical array of crystal optical axes began to freeze to the turbid crystalline ice (Figs. 3, 4). At the beginning the dynamics the ice thickness increment was 0.4 cm per day in both water bodies (from 13 to 25.01.2012), and on 15 January its thickness reached 4.2 and 4.5 cm in the water bodies of Amendy and Żabie Doły S, respectively. On 14 February the ice cover on the Amendy water body was 33.5 cm thick, and on the Żabie Doły water body it was 34.5 cm thick. During the period from 26 January to 14 February 2012 ice thickness increment was on average 1,5 cm per day in both water bodies (Figs. 3, 4, Tab. 3).

As a result of unblocking of the zone circulation Poland was again under the influence of warm, humid polar-maritime air masses coming from a north-westerly direction. This cyclonic circulation contributed to a gradual increase in the air temperature which began on 15 February 2012 (Fig. 2). The atmospheric fronts passing over Poland were accompanied by heavy snowfall, which led to a cover of snow forming on the ice and its maximum thickness was slightly above 15.0 cm on both water bodies. At that time there was a slight increase in the ice thickness from the ceiling, caused by the freezing of a snow slush layer which had gathered on the ice. The ice thickness in both cases increased to 36 cm, reaching its maximum in that winter season (Figs. 3, 4).

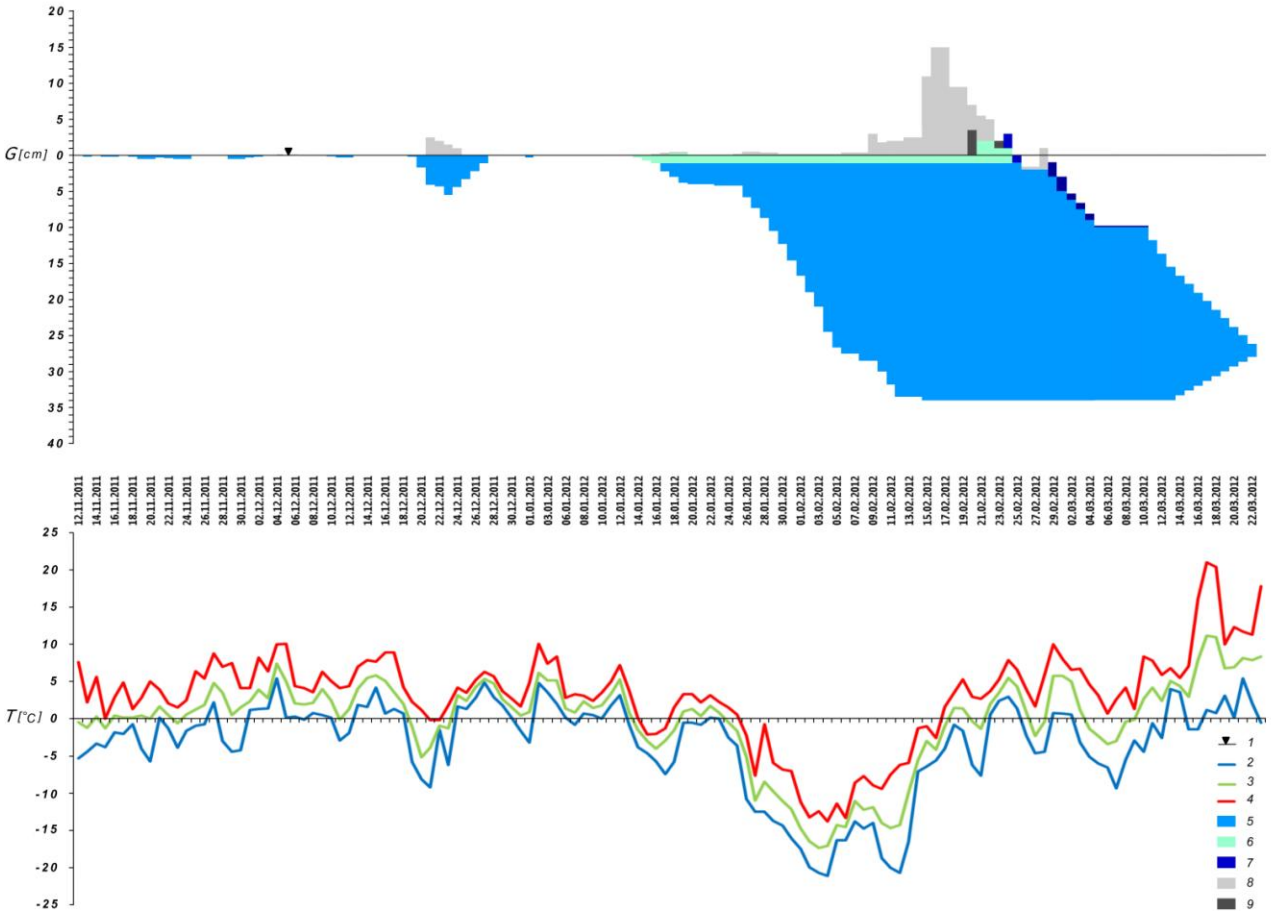

Fig. 3. The ice cover structure of the Amendy water body in the ice season of 2011/2012
1 – height of the upper part of the ice at the beginning stage, 2 – minimum daily air temperature, 3 – average daily air temperature, 4 – maximum daily air temperature, 5 – crystal ice, 6 – snow ice, 7 – water, 8 – snow, 9 – slush

Table 3. Dynamic ice thickness changes in the water bodies

Period [2011/2012]	Average daily air temperature from the meteorological station of Faculty of Earth Sciences of University of Silesia (°C)	Average minimum daily air temperature from the meteorological station of Faculty of Earth Sciences of University of Silesia (°C)	Average ice thickness (cm)	Average change of ice thickness (cm/day)
11.11. – 30.11.	0.9	-2.4	A 0.3	A – 0.0
			Ż 0.3	Ż – 0.0
01.12. – 18.12.	3.4	0.9	A 0.1	A – 0.0
			Ż 0.1	Ż – 0.0
19.12. – 23.12.	-2.5	-6.2	A 3.2	A – 0.7
			Ż 2.6	Ż – 0.7
24.12.–12.01.	3.1	1.3	A 0.6	A – -0.2
			Ż 0.4	Ż – -0.2
13.01.–25.01.	-0.7	-2.8	A 2.7	A – 0.4
			Ż 3.1	Ż – 0.4
26.01.–14.02.	-12.3	-15.9	A 22.1	A – 1.5
			Ż 22.3	Ż – 1.5
15.02.–21.02.	-1.0	-4.6	A 34.3	A – 0.4
			Ż 34.8	Ż – 0.2
22.02.–03.03.	2.8	-0.5	A 31.8	A – -0.9
			Ż 31.9	Ż – -0.8
04.03.–09.03.	-1.8	-5.9	A 24.2	A – -0.4
			Ż 25.1	Ż – -0.3
10.03.–23.03.	6.4	0.7	A 12.0	A – -1.7
			Ż 12.5	Ż – -1.8

Water bodies: A – Amendy; Ż – Żabie Doły S

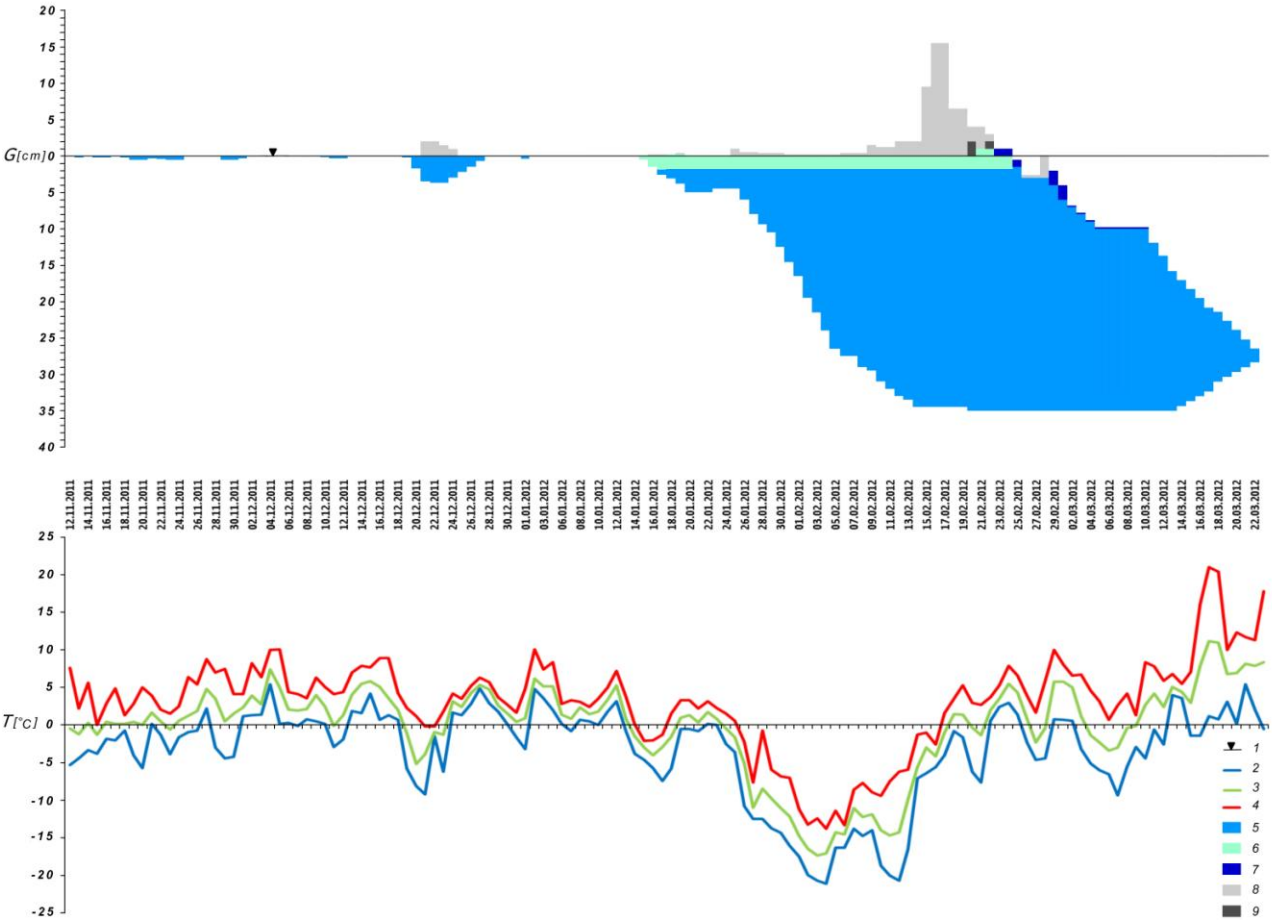

Fig. 4. The ice cover structure of the Żabie Doły S water body in the ice season of 2011/2012
1 – height of the upper part of the ice at the beginning stage, 2 – minimum daily air temperature, 3 – average daily air temperature, 4 – maximum daily air temperature, 5 – crystal ice, 6 – snow ice, 7 – water, 8 – snow, 9 – slush

The ice cover commenced the disintegration process from 22 February 2012 (Fig. 2). The positive air temperature maintained in the area caused the gradual thawing of the snow cover lying on the ice, and then a ceiling ablation of the snow ice took place (Figs. 3, 4). In the beginning the ablation rate was slow because the temperature oscillated around 0°C, with some periods decreasing to negative values during day and night (Fig. 2, Tab. 3). The average daily temperature began to rise a few degrees above zero from 10 March 2012, due to unblocking of the cyclonic zone circulation. This increase in temperature from the middle of March contributed to the dynamic ice ablation on both water bodies (Figs. 2, 3, 4).

An incomplete cover of ice s was maintained until 21 March 2012, although presence of the partial ice covers was observed for one day. Ice disappeared completely from both water bodies on 23 March. During the period from 10 to 23 March 2012 the ice melted at a rate of almost 2 cm per day in both cases (Tab. 3).

The average ice thickness of the Amendy water body was 14.7 cm during the ice phenomena, and 18.8 cm when there was a complete cover. The Żabie Doły S water body had slightly higher values with an average ice thickness between 14.9 and 19.1 cm (Figs. 3, 4).

The daily ice thickness measurements performed for over four months were compared with the average daily air temperature taken from the meteorological station at the Faculty of Earth Sciences (University of Silesia) located 17 km away. The calculated values for the correlation coefficients were strong and inversely proportional ($r = -0,84$ ($p<0,001$) – Amendy; $r = -0,87$ ($p<0,001$) – Żabie Doły S), which confirms there is a strong relationship between the changes in the ice thickness of the water bodies with the change in average daily air temperature. A decrease in air temperature caused a corresponding increase in ice thickness and vice versa.

5. Discussion

Daily observations and measurements of ice phenomena on the lakes and water bodies in Poland are rare. Only a few small water bodies located in the Silesian Upland were included in the detailed monitoring of ice formation (RZĘTAŁA

& RZĘTAŁA, 2009, 2012; RZĘTAŁA & SOLARSKI, 2011; RZĘTAŁA, 2012, 2014; MACHOWSKI, 2013, 2014; SOLARSKI, 2017). These water bodies are similar in several respects. They were formed as a result of human activity, and are characterized by their small size and are all located in municipal-industrial areas (RZĘTAŁA & RZĘTAŁA, 2009; MACHOWSKI, 2013; SOLARSKI, 2017). In the winter season of 2011/2012, in addition to the water bodies which have been discussed in detail daily investigations were also performed on the dynamics of ice formation on the water body in Czeladź (RZĘTAŁA, 2012, 2014) and in Katowice (MACHOWSKI, 2013, 2014). As found in this investigation RZĘTAŁA (2012, 2014) the ice phenomena on the water body in Czeladź lasted from 13 November to 20 March, and a complete and durable ice cover was formed on 16 January. The maximum ice thickness measured by the author was 34 cm and occurred at the turn of the second and third weeks of February (RZĘTAŁA, 2012, 2014). According to MACHOWSKI (2013, 2014) the beginning of the ice phenomena on the water body located in Katowice was on 19 November, and had completely disappeared by 21 March 2012. The durable and complete ice cover, in the case of the water body located in Czeladź, was formed on 16 January. The maximum ice thickness in that season was 37 cm, which the author measured at the beginning of the second week of February (MACHOWSKI, 2013, 2014). The study results mentioned above, and presented in RZĘTAŁA (2012, 2014) and MACHOWSKI (2013, 2014) are similar to those which were observed on the Amendy and Żabie Doły S water bodies. All four water bodies reacted in a similar way to changes in air temperature in the freezing phase, which results from similar morphometric parameters which besides the atmospheric conditions, decide about a rate of freezing of the water areas (LEPPÄRANTA, 2009, 2015). The ice phenomena disappeared almost simultaneously from all water bodies because this process depends mainly on external factors such as solar radiation and air temperature (KIRILLIN ET AL., 2012). The maximum ice thickness measured in all water bodies occurred in the second half of February as a consequence of significant decrease in the daily air temperature (RZĘTAŁA, 2012, 2014; MACHOWSKi, 2013, 2014; Figs. 3, 4). The thickness exceeded 30 cm, and the difference between these two water bodies did not exceed 3 cm (RZĘTAŁA, 2012, 2014; MACHOWSKI, 2013, 2014, Figs. 3, 4). In all cases the main phase of the ice formation was the complete and durable ice cover persisting for several dozen days (RZĘTAŁA, 2012, 2014; MACHOWSKI, 2013, 2014; Figs. 3, 4). The investigation results presented above show that both the water bodies from Bytom and the Czeladź water body (RZĘTAŁA, 2012, 2014) and Katowice (MACHOWSKI, 2013, 2014) are characterized by a quasi-natural ice regime.

6. Conclusions

It is possible to draw a few conclusions from these investigations:

1) the beginning of the observed ice phenomena commenced on 13 November 2011 and had completely disappeared by 23 March 2012;

2) in both water bodies the following ice formation phases were observed: the shore ice, a partial incomplete and complete ice cover, differentiated on the basis of the percentage area of the water body that was covered with ice;

3) the main ice formation phase in the studied water bodies constituted complete ice cover persisting for 71 days, which was 74% of the number of days with ice phenomena. The durable and complete ice cover was maintained from 16 January to 22 March 2012;

4) the maximum ice thickness in both water bodies was 36 cm, was measured in the third week of February, which is a typical for lakes and water bodies located in the moderate climatic zone;

5) the ice cover of the water bodies that were monitored was formed mainly as a result of the bottom ice growth of crystalline ice characterized by the vertical orientation of the optical axes of crystals;

6) due to the short period of thick snow cover there were no observations of the process of denting ice by snow, and the ceiling freezing was limited to an incrementally thin layer of turbid ice formed from the water-snow slush layer. In both water bodies the thickness of this did not exceed 5% of the maximum ice thickness in that season;

7) the calculated Spearman's correlation coefficients indicate that a strong inverse relationship is taking place between the daily air temperature changes and the daily changes in the ice thickness. For the Amendy water body this relationship was r=-0.84, and for that of Żabie Doły S r=-0.87, for p<0,001 statistical significance;

8) the maximum daily increment of ice thickness was 3.5 cm (Amendy) and 3.0 cm (Żabie Doły S), and the maximum daily loss of ice thickness was 2.0 cm (Amendy, Żabie Doły S);

9) on the basis of this investigation it can be stated that the water bodies included in the ice monitoring are characterized by a quasi-natural ice regime.

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