Natural and anthropogenic influences on ice formation on various water bodies of the Silesian Upland (southern Poland)

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Abstract: The aim of the study was to identify patterns of ice-related phenomena on 39 selected anthropogenic water bodies in the Silesian Upland in southern Poland. The core research was conducted in the winter season of 2009/2010, between December and March. Field measurements and observations were conducted every two days during the freezing and thawing phases and every four days at the time of continuous ice cover. Data were interpolated to cover days without observations. Differences in the ice cover phenology on these water bodies were caused by natural conditions (morphometric and hydro-meteorological) and human activity (thermal pollution). Two principal groups of anthropogenic water bodies were identified in terms of the ice phenomena: lakes and ponds with a natural or quasi-natural pattern of ice phenomena and water bodies featuring various degrees of human impact. The thickness of the ice-cover was found to vary, which was a source of great danger to the users of the water bodies in the winter season.

Key words: ice phenomena, ice cover, water body, Silesian Upland

Introduction

Ice phenomena in lakes and reservoirs have recently attracted increasing interest from researchers both in Poland and abroad. Most studies dealing with this issue focus on long-term regularities related to ice cover phenology and other ice cover descriptive parameters. Such descriptors as the average dates on which ice occurs and disappears, the number of days with ice cover and its average and maximum thickness are usually recorded. In most cases, correlations are determined between these data and average air temperatures in the region of the world in question. Presented in this manner, ice parameters are considered to be one of the indicators that reflect contemporary climate change (Livingstone 1999; Magnuson et al. 2000; Hodgkins et al. 2002; Lenormand et al. 2002; Yoo and O'Dorico 2002; Marszelewski and Skowron 2006, 2009; Johnson and Stefan 2006; Skowron 2006, 2009; Jensen et al. 2007; Choiński et al. 2009; Ghanbari et al. 2009; Livingstone et al. 2009; Fang and Stefan 2009; Sziwa and Jańczak 2009; Mishra et al. 2011; Mu-

delsee 2011; Weyhenmeyer et al. 2011). A much smaller number of studies touch upon detailed parameters associated with ice during short periods (e.g. a single winter season). In these studies, the main focus is on the correlation between the average daily air temperature and the rate at which the water body in question freezes over or thaws (Solarski et al. 2010), daily increments in ice cover (Rzętała and Solarski 2011), the analysis of the types of ice that form (Leppäranta 1983, 2009; Leppäranta et al. 2003; Rzętała and Rzętała 2009), ice cover movements (Grześ 1974; Reinart and Pärn 2006; Aihara et al. 2010), spatial variations in its thickness and the impact of broadly defined anthropogenic pressure on ice variables (Choiński et al. 2006; Choiński 2007a, 2007b, 2010; Jankowski et al. 2009; Machowski and Ruman 2009; Solarski and Pradela 2010). Despite large numbers of anthropogenic lakes worldwide exposed to various degrees of anthropopressure, the available research into ice-related phenomena in such water bodies must be seen as exceptionally modest (as opposed to research on ice-phenomena in natural lakes free from anthropogenic

influences). This study joins a trend towards detailed research on ice-related phenomena in anthropogenic lakes, a topic which had previously rarely been studied. The purpose of the study was to determine the regularities determining ice characteristics in water bodies subject to varied anthropogenic pressure – ranging from those situated in quasi-natural areas to those in urban and industrial districts. Safety reasons constituted another important aspect of this assessment in view of the hazards involved in the use of frozen anthropogenic water bodies.

In the light of an existing scientific opinion that freezing processes on water bodies exposed to anthropopressure are entirely distorted, a hypothesis was proposed for the purpose of this study that in areas exposed to anthropopressure, the patterns of these processes vary across an entire spectrum from purely natural to entirely distorted. It was hypothetically assumed that it would be possible to identify, in areas of anthropopressure, water bodies whose ice covers would be safe to use.

The research was conducted in one of the areas of both Poland and Europe that has been subject to

the most extensive anthropogenic change. It involved a variety of water bodies that provided a wealth of material on freezing effects and allowed a comparison with data from other parts of the world found in published research.

Study area

The anthropogenic water bodies selected for study purposes are situated in the Silesian Upland (southern Poland), an area that has been significantly transformed with respect to all components of the natural environment as a result of industrial activity and urban development (Fig. 1). Moreover, this is the area in Poland where the largest cluster of anthropogenic water bodies of varied origin is found, these forming an anthropogenic lake district of very special character (Rzętała 2008; Rzętała and Jaguś 2011). The water bodies, selected from 2405 anthropogenic lakes and ponds on record (in 2005) within the Silesian Upland with a combined area of 60.8 km², ranged from the entirely man-made to ones that evolved as an inadvertent result of human activities.

Fig. 1. Locations of anthropogenic water bodies studied in the Silesian Upland: 1 – province boundaries, 2 – macroregion boundaries, 3 – mesoregion boundaries, 4 – rivers, 5 – water bodies studied (numbering as in Table 1), 6 – towns

The main factor determining which water bodies were selected for study was their diversity, i.e. the inclusion of water bodies of varying origins and exhibiting different morphometric and hydrological characteristics (Table 1). The lakes varied also in terms of their chemical and physical properties.

Methods

The studies of ice on anthropogenic water bodies in the Upper Silesia region were carried out in the winter season of 2009-2010. In total 39 water bodies were monitored. Measurements and observations

Table 1. Certain morphogenetic, hydrogenetic, morphometric and physico-chemical parameters of the selected anthropogenic lakes in the Silesian Upland (hydrological year 2010, winter half)

No.	Lake	Lake origin	Hydrologic type	Area	Volume	Conductivity (min÷max)
				ha	dam ³	µS·cm ⁻¹
1	Akwen (Makoszowy)	former extraction pit	non-drained	2.4	62.3	700÷1063
2	Amendy	former extraction pit	non-drained	1.3	21.4	326÷372
3	Balaton	former extraction pit	drained	7.4	68.8	437÷528
4	Brantka	subsidence bowl	drained	21.3	625.7	979÷1256
5	Brzeziny	artificial bowl	drained	0.9	9.6	2280÷2918
6	Dzierżno Duże	former extraction pit	flow-through	587.2	66000.0	5195÷6663
7	Farskie	subsidence bowl	flow-through	12.3	149.5	2070÷3293
8	Gliniok	subsidence bowl	drained	2.2	37.0	688÷782
9	Grunfeld	former extraction pit	non-drained	3.9	179.0	401÷478
10	Hubertus II	former extraction pit	drained	18.2	249.4	521÷568
11	Kajakowy	polygenetic	flow-through	10.0	244.4	686÷837
12	Kamieniec	dyke-type	flow-through	3.2	25.1	678÷895
13	Kozłowa Góra	dam-lake	flow-through	550.0	13050.0	338÷448
14	Kuźnica Warężyńska	former extraction pit	flow-through	536.0	39120.0	457÷535
15	Leśny	subsidence bowl	drained	33.4	1011.5	1243÷2050
16	Łąka	polygenetic	flow-through	13.1	292.0	729÷827
17	Maroko	polygenetic	non-drained	8.1	109.5	680÷787
18	Moczury	subsidence bowl	drained	14.5	231.2	1061÷1204
19	Morawa	former extraction pit	drained	34.7	559.1	392÷461
20	Nakło-Chechło	former extraction pit	drained	80.1	1200.0	164÷187
21	Niezdara N	polygenetic	flow-through	0.2	no data	269÷519
22	Niezdara S	polygenetic	non-drained	0.1	0.2	416÷786
23	Ostroznica	dyke-type	flow-through	4.1	21.5	198÷248
24	Pod Borem	artificial bowl	drained	1.9	no data	14133÷16765
25	Pogoria III	former extraction pit	flow-through	211.2	12000.0	567÷675
26	Przetok	former extraction pit	drained	1.5	16.8	1171÷1833
27	Rogożnik Duży	former extraction pit	flow-through	23.7	272.9	579÷741
28	Rozlewisko Bytomki	subsidence bowl	non-drained	1.2	14.3	2192÷3209
29	Skalka	artificial bowl	non-drained	5.9	110.3	371÷439
30	Smrodlok	subsidence bowl	non-drained	2.9	46.4	907÷1046
31	Somerek	artificial bowl	drained	4.2	no data	6252÷7254
32	Sośnica-Makoszowy	artificial bowl	drained	4.2	no data	53638÷72262
33	Szczygłowice	subsidence bowl	drained	21.0	471.2	378÷505
34	Szkopka	polygenetic	non-drained	1.4	21.8	546÷827
35	Trupek	former extraction pit	non-drained	0.7	8.1	1014÷1290
36	Trzy Stawy (Miechowice)	dam-lake	flow-through	0.3	2.7	776÷1152
37	Zbiornik przy Leśnej	subsidence bowl	non-drained	0.3	2.0	2170÷3827
38	Żabie Doły N	polygenetic	drained	9.4	140.4	2306÷3016
39	Żabie Doły S	subsidence bowl	non-drained	2.6	43.3	1034÷1209

started on 10 December 2009, i.e. in the period directly preceding the time when the average daily air temperatures fell below 0°C, and finished on 27 March 2010, i.e. after ice had disappeared from all the water bodies. Measurements were carried out every two days during the freezing and thawing periods; and every four days during the period when continuous ice cover was present. Data were interpolated to cover days without observations. The following parameters were recorded during measurements: thickness of ice cover, types of ice present, forms of ice (aufeis on shores, shore ice, partial ice cover), water temperatures in the near-surface layer and other parameters (snow cover, water present on the ice cover). In the initial ice formation phase, ice thickness was directly measured with a caliper at a location where the ice had been broken or with a simple ice thickness measuring implement if the ice was thicker. The thickness of the snow cover or the water present on the ice cover was also measured on every occasion. In order to determine the spatial variation in the thickness of ice cover in 30 water bodies, up to several dozen holes were drilled whose locations were determined using a portable GPS receiver.

The air temperature measurements included in the study were obtained from the weather station of the Faculty of Earth Sciences at the Silesian University at Sosnowiec. The average daily temperature recorded during the ice phenomena period ranged from -15.9°C to 13.9°C, while the average minimum temperature during the field study period was -5.8°C. The average air temperature in the studied winter season (months from November to April) was 1.8°C, allowing us to describe those six months as average against data from the years 2000-2011 obtained from the IMGW station in Katowice. In that period the lowest average temperature for the winter six months was recorded in the hydrological year of 2006, and amounted to 0.2°C, while the highest was recorded in the hydrological year of 2007 and amounted to 5.2°C. Precipitation in the hydrological year of 2010 was recorded on numerous occasions and its total depth during the ice period was 158 mm. The average monthly wind speeds did not exceed single metres per second and the monthly maximum remained under 20 m·s⁻¹. Western winds dominated. There were several cases of fog.

Results

The field study produced the following results (Figs 2-4, Table 2):

- The dates on which ice cover first occurred in water bodies differed significantly; the difference could be up to 40 days (from 13 December 2009 to 24 January 2010),
- The time that elapsed from the first occurrence of ice to the formation of a continuous ice cover varied (small water bodies were already completely frozen 24 hours after average daily air temperatures had dropped below 0°C; for some water bodies, this period exceeded a fortnight),
- For large water bodies with significant wave activity, a characteristic initial form of ice formation was aufeis which was mostly present in places splashed by waves. This was observed for several days before shore ice or continuous ice cover formed,
- The maximum recorded thickness of ice cover in individual completely or partially frozen over water bodies ranged from around 2 to nearly 30 centimetres,
- Spatial variation in the thickness of the ice cover, which reached more than a dozen centimetres (up to 14 cm), resulted from the prolonged presence of snow upon the continuous ice cover and uneven freezing of snow ice,
- In many water bodies studied, permanent unfrozen areas were present despite the thick continuous ice cover that formed. These resulted from the oxygenation of limnic water using an underwater oxygenation system or from wastewater discharges,
- In water bodies that were affected by thermal pollution, ice cover either did not occur at all or took the form of an ice blanket (or an ice cover no thicker than 2 cm) even when average daily air temperatures were very low (around -15°C),
- The water bodies that did not freeze and those that featured persistent unfrozen areas served as water-bird sanctuaries,
- The maximum difference in the dates of disappearance of the ice cover was 13 days; it first disappeared on Lake Dzierżno Duże (14 March 2010), while the last water body to thaw was Lake Ostroźnica (27 March 2010).

The water bodies in the Silesian Upland can be classified into two main types on the basis of the research carried out. The largest group form the water bodies on which continuous ice cover was present for more than 80 days, i.e. around 80% of the time during which ice occurred. For these water bodies, the ice regime was close to the natural one. This group includes those water bodies that can be broadly defined as clean

Table 2. Parameters describing the spatial variation in ice cover thickness (in centimetres) in selected anthropogenic lakes in the Silesian Upland

No.	Water body	Maximum	Minimum	Average	Date of measurement
1	Akwen	26.0	19.0	22.3	15.02.2010
2	Amendy	20.0	13.5	15.9	23.01.2010
3	Balaton	24.0	14.5	19.0	24.02.2010
4	Brantka	20.0	13.5	16.7	18.01.2010
5	Brzeziny	23.0	12.0	18.8	29.01.2010
6	Dzierżno Duże	no data			
7	Farskie	26.5	17.0	22.3	15.02.2010
8	Gliniok	21.5	16.0	18.9	06.02.2010
9	Grunfeld	27.5	21.5	24.1	18.02.2010
10	Hubertus	27.5	18.5	22.1	24.02.2010
11	Kajakowy	31.0	22.0	25.7	18.02.2010
12	Kamieniec	22.0	12.5	19.1	21.02.2010
13	Kozłowa Góra	no data			
14	Kuźnica Warężyńska	no data			
15	Leśny	29.5	17.0	23.1	15.02.2010
16	Łąka	32.0	18.0	26.2	18.02.2010
17	Maroko	25.0	17.5	21.2	07.02.2010
18	Moczury	27.0	16.0	19.5	16.02.2010
19	Morawa	31.0	19.0	23.7	19.02.2010
20	Nakło-Chechło	no data			
21	Niezdara N	no data			
22	Niezdara S	23.0	19.0	21.0	17.02.2010
23	Ostrożnica	30.5	19.0	23.6	17.02.2010
24	Pod Borem	no data			
25	Pogoria III	no data			
26	Przetok	23.0	14.5	19.2	29.01.2010
27	Rogożnik Duży	33.0	19.0	25.8	24.02.2010
28	Rozlew. Bytomki	20.0	13.5	17.1	22.01.2010
29	Skalka	24.5	17.0	19.4	07.02.2010
30	Smrodlok	25.5	14.0	20.0	06.02.2010
31	Somerek	no data			
32	Sośnica-Makoszowy	no data			
33	Szczygłowice	27.5	17.0	23.9	22.02.2010
34	Szkopka	15.0	10.5	13.3	09.01.2010
35	Trupek	27.0	16.0	18.9	06.02.2010
36	Trzy Stawy	9.0	5.0	7.1	08.01.2010
37	Zbiornik Przy Leśnej	24.0	11.0	16.9	22.01.2010
38	Żabie Doły N	23.0	17.0	18.7	29.01.2010
39	Żabie Doły S	22.0	18.0	19.1	28.01.2010

(no thermal pollution), including the largest ones such as the Kuźnica Warężyńska, Pogoria III, Kozłowa Góra and Nakło-Chechło. In small water bodies with quasi-natural ice regimes, the duration of continuous ice cover was slightly shorter than for large water bodies, largely owing to the slightly smaller thermal inertia of the waters they contain. These water bodies responded to changes in air temperature faster (Fig. 2). This group includes also the water bodies whose ice regime

exhibited anthropogenic impact. In these water bodies, partial ice cover was present for a significant part of the period during which ice occurred. A characteristic feature of these water bodies was persistent unfrozen areas that were recorded in zones where warmer water flowed into the water body in question (Brantka, Farskie, Łąka among others) or where limnic water was artificially oxygenated (Maroko, Moczury). The second type included water bodies with a

Fig. 2. Ice cover on selected water bodies in the Upper Silesia region in the winter season of 2009-2010: 1 – no ice cover, 2 – aufeis on shores, 3 – shore ice, 4 – partial ice cover, 5 – continuous ice cover, 6 – floes, 7 – average daily air temperature

Fig. 3. Average and maximum thickness of the selected anthropogenic water bodies ice cover: 1- maximum thickness, 2 – average thickness

completely distorted ice regime where ice was absent or occurred only incidentally when very low average daily air temperatures persisted for a long time. During the entire winter season, these water bodies were supplied with heated mine water (Somerek, Sośnica, Pod Borem). Ice only appeared in the coastal zones at the end of January (23-24 January) during a period when average daily air temperatures remained below -10°C for several days. The appearance of shore ice on the Somerek water body was preceded by the formation of aufeis on shores which persisted for several days. Shore ice persisted for one day, and subsequently a thin (up to 2 cm) partial ice cover formed with a large unfrozen area in the zone where water from a mine was discharged into the water body. Partial ice cover persisted for 10 days and then thawed completely within one day. Just two ice formation phases were also observed on the Sośnica-Makoszowy water body – shore ice formed persisting for 2 days and partial ice cover formed in the form of a thin ice blanket (up to several millimetres thick) which lasted for 5 days. In the case of Lake Pod Borem, a heated mine water sedimentation tank situated on the boundary of Zabrze and Bytom, no ice cover was recorded during the entire winter season and the surface water temperature did not drop below 7°C even when the average daily air temperatures reached -15°C (Fig. 2). An important fact to note is that some of these warm water bodies served as water-bird sanctuaries and thus constituted

peculiar winter environmental niches.

During the 2009-2010 winter season, significant variation was recorded with respect to the average and maximum thickness of ice cover in the water bodies studied. The greatest maximum thickness (29.5 cm) was recorded for the Kuźnica Warężyńska and Ostrożnica water bodies, while the smallest thickness (13.0 cm) was observed in the Niezdara N water body. The average thickness of ice cover ranged from 5.5 cm in the Niezdara N water body to over 20 cm for the Kozłowa Góra and Kuźnica Warężyńska water bodies. The smallest difference between these parameters was recorded in the Rozlewisko Bytomki water body (6.1 cm); similar values were observed in the Dzierżno Duże (6.3 cm), Moczury (6.6 cm) and Hubertus (6.9 cm) water bodies. On the other hand, significant differences of around 13 cm were present in the Maroko, Farskie and Morawa water bodies (Fig. 3).

Results of studies on spatial variation in the ice cover thickness are presented on isopachyte maps (Fig. 4). The largest differences between minimum and maximum ice cover thickness were found in the Rogoźnik Duży and Łąka water bodies; these reached 14 cm. The smallest differences were present in the Niezdara S, Szkopka, Trzy Stawy and Żabie Doły S water bodies; they amounted to around 4 cm. The thickness of the ice cover always varied within the same lake (Table 2).

Fig. 4. Variation in ice cover thickness in selected anthropogenic water bodies: A – Leśny (15 February 2010), B – Smrodlok (6 February 2010), C – Grünfeldt (18 February 2010), D – Balaton (24 February 2010), E – Skalka (7 February 2010), F – Kamieniec (21 February 2010), G – Rogoźnik Duży (24 February 2010), 1 – water body shoreline, 2 – isopachytes, 3 – isles, 4 – drilling points

Discussion

Collected observations on freezing phenomena have led to a number of conclusions as to the specific features associated with lake freezing in areas with considerable anthropogenic influences. The fact that the study was confined to a single region with relatively uniform natural and human-related conditions facilitated comparisons. However a lack of similar research elsewhere in Poland, Europe and the world made it dif-

ficult to draw up a synthesis of the material collected. As a result of the highly varied exposure to anthropopressure in the water bodies of the Silesian Upland, the freezing phenomena can range from phenomena identical to those found in natural lakes, to inhibited phenomena and finally to an entire absence of freezing in highly thermally polluted anthropogenic water bodies. The study revealed a number of lakes entirely devoid of ice due to their thermal pollution. Normally these lakes had volumes lower than one million cubic metres al-

though similar freezing-restricting processes were also observed in water bodies with volumes of dozens of millions of cubic metres. One such lake in the Silesian Upland is Zbiornik Rybnicki (50°08'25"N, 18°29'58"E) and it stands out in the moderate climate zone in terms of the scale of its anthropogenic temperature change (Eloranta 1983; Drwal and Lange 1991; Chen et al. 2000; Beznosov and Suzdaleva 2001). At a regional scale the issue of the warm waters in Zbiornik Rybnicki was flagged by Jankowski and Kuczera (1992), while Rzętała (2008) determined that the scale of change there was a rise of up to more than ten degrees centigrade above natural in winter which caused the lack of ice cover. The anthropogenic exposure and the relatively small area of the Silesian Upland cause poor legibility and a lack of spatial correlation patterns in the spatial variability of ice-related phenomena, as identified by Marszelewski and Skowron (2005) for lakes in the moderate transitional climate of Central Europe and expressed as an eastwards growth of ice thickness. Unlike in large lake districts covering large areas of territory, such those found in Finland, where spatial relationships are found in terms of the onset and end of ice-related phenomena (Palecki and Barry 1986), such patterns are hard to identify in the small Silesian Upland. Most probably, here ice thickness differences between each lake are primarily determined by morphometric differences between the water bodies and the hydrometeorological conditions in their surroundings. A characteristic feature of ice cover in anthropogenic water bodies was the spatial variation in ice cover thickness; there were also differences recorded between individual water bodies with respect to this variation. These data demonstrate that no regularities were identified with respect to spatial variation in the ice cover thickness with the exception of differences in the ice thickness of up to several dozen per cent in relation to the maximum thickness (Table 2). Similar results were reported by other authors in both lowland and mountain lakes in Poland (Choiński et al. 2006; Choiński 2007a, 2007b, 2010). Uneven freezing of snow ice was probably a major reason for the significant spatial variation in ice cover thickness. The top-side thickness growth is primarily driven by a freezing-on of atmospheric precipitation and sedimentation of various kinds. As a result the ice cover features various forms of cover (such as multilayer ice cover typically with water or various kinds of snow) and processes (freezing-on at the top or freezing-on of the top-layer's bottom while the top of the bottom layer is thawing) (Solariski and Pradela 2010; Piątek et

al. 2010). Early freezing stages were dominated by bottom-side freezing processes, which were replaced by top-side freezing processes once the insulating role of the ice cover was established. The topside freezing-on processes occurred even as the bottom side of the ice cover was thawing due to the increasing temperatures of the water recharge in the water body (Rzętała and Solariski 2011). The ice cover also gained in thickness as a result of freezing over of water pouring through the cracks under the weight of the snow cover (snow depth about 20 cm). The snow layer was soaked with water and subsequently froze owing to low air temperatures. This process progressed unevenly within individual water bodies, leading to significant differences in ice cover thickness – even for small water bodies. As a result, differences in ice cover thickness within the water bodies studied increased together with its duration. Leppäranta (1983, 2009) observed a similar role of ice cracking in his ice study, while Aihara et al. (2010) pointed to changes in the water level in a frozen lake and to water temperature changes as drivers of the horizontal and vertical extent and structure of the ice cover. It is worth noting that lakes with high mineral concentrations, which in the Silesian Upland can reach up to several dozen grams per cubic decimetre, are characterised by ice process sequences different from natural freshwater lakes. The differences include the overall ice structure, inhomogeneous crystallographic structures and often lower mechanical strength, but not ice thickness, which remains essentially the same in various unpolluted water bodies. The differing features are also found, if to a considerably lower extent, in frozen sea water or slightly salty waters, which is highlighted by Leppäranta et al (2003) who compare results of research in the Gulf of Finland and in a number of Estonian lakes.

Conclusions

The study allows one to draw a number of conclusions about the factors determining the variability in the ice conditions on anthropogenic lakes and ponds in the Silesian Upland, namely:

1. Differences in the ice-related phenomena in water bodies in the Silesian Upland are driven both by natural and by human influences.
2. There are two main types of water bodies found in the region, i.e. (i) lakes with a natural or quasi natural course of ice-related phenomena and (ii) lakes with various degrees of anthropogenicity. Typically the influence of anthropopressure results in:

a delayed onset and accelerated disappearance of ice phenomena (or even the lack of them), thinner ice and its greater diversity within one lake, as well as a much more frequent incidence and spread of unfrozen sites of peat bog thermal activity.

3. The varied ice thickness within each lake causes great hazards to various human activities, such as angling and ice sailing on the frozen lakes.

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