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Seasonal changes in the concentrations of dissolved oxygen in the lakes of the "Bory Tucholskie" National Park

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Abstract: The article presents the results of the examinations of dissolved oxygen vertical distribution (DO) in the deepest places of the lakes conducted at different times in the years 2003-2005, and even earlier. The authors draw particular attention to severe oxygen deficits in the deepest places of the lakes, both those deep and shallow lakes despite the fact that they are not so exposed to anthropopressure. They also point out to the similarity of the course of oxygen curves in the same lakes and seasons in consecutive years, and also differences between particular lakes. They have also determined minor correlation between the mean concentration of DO in the vertical distribution and the duration of period with the ice cover (R^2=0.78).

Keywords: lakes, dissolved oxygen, hypoxia, anoxia

Introduction

Concentration of dissolved oxygen (DO) depends upon physiochemical and biological conditions of lake waters. Polimictic lakes should contain similar amounts of DO in the entire vertical distribution. Stratified lakes reveal its more diverse amounts. Increase in lake productivity and eutrophication is accompanied by a growing difference between the concentration of dissolved oxygen in the epilimnion and hypolimnion. The distribution of DO in the clinograde layer is conditioned by biological processes. Oxycline becomes more noticeable and its deficit or lack becomes conspicuous in the hypolimnion. Low DO content is defined as hypoxia (with DO concentration from 2 to 1 $mg \cdot dm^{-3}$) or anoxia (with DO <1 $mg \cdot dm^{-3}$). The dependencies between the content of DO and lake trophy were presented by Horne and Goldman (1994), among others. Considerable variations in DO concentration depending on the lake depth and the range of the euphotic zone were established. They result from different amounts of biomass and also the course and intensity of photosynthesis and respiration (Wetzel 2001).

Investigation range and methods

This work was based on the results of the measurements of DO concentration and water temperature in the lakes located in the "Bory Tucholskie" National Park. The authors selected the lakes which are strongly diversified with respect to morphometry, including maximal depths in particular (from 43 m in Lake Ostrowite to 6.2 m in Lake Wielkie Gacno) and areas (from over 280 to 8 h, Tab.1). The examinations were conducted in the deepest places of the lakes, from the surface to the bottom with intervals every 1 m, in consecutive years 2003 – 2005, and in the winter of 2006. The measurements were carried out by means of oxygen sound ProfiLine Oxi 197 produced by Wissenschaftlich-Technische Werkstätten GmbH with fitting and mixer for deep measurements.

The results of the investigations were supplemented by other materials, including those from the 1960s (obtained from the Inland Fisheries Institute in Olsztyn), and from the 1990s (Jutrowska, Marszelewski 1998, Gwoździński et al. 2001). The authors would also like to thank dr E. Nowicka who offered data from summer seasons for several lakes. Altogether the

Table 1. Selected morphometric data of the analysed lakes.

Lake	W m a.s.l.	P ha	D_{max} m	S_{max} m	L	H_{max}	H_{sr}	V $m^3 \cdot 10^3$
Ostrowite	124.2	280.7	3900	1050	3.7	43.0	10.7	29989.8
Płęsno	121.0	47.8	2170	370	5.8	11.0	4.7	2254.1
Krzywce Wielkie	121.0	26.5	1100	450	2.4	15.0	6.5	1724.1
Zielone	124.1	25.5	1030	328	3.1	20.5	9.0	2293.4
Gacno Wielkie		14.2	1015	259	3.9	6.2	3.1	443.5
Nierybno	122.5	9.0	840	160	5.3	8.3	4.2	380.1
Główka	121.6	8.0	314	236	1.3	11.0	3.7	299.5

Symbols: W – height of water table; P – area; D_{max} – maximum length; S_{max} – maximum width; L – elongation (D_{max}/S_{max}); H_{max} – maximum depth; H_{sr} – mean depth; V – volume.

Source: unpublished data of the Inland Fisheries Institute in Olsztyn, Poland and topographic maps at the scale 1:25000 Konarzyny and Męcikał sheet.

analyses consider the results of the investigations of approximately 100 thermo-oxygen distributions, out of which nearly a half has been presented in a graphic form in the study.

Results

The concentration of dissolved oxygen in the lakes located in the "Bory Tucholskie" National Park varies considerably in particular months and seasons. This is especially noticeable with respect to the concentration of oxygen over the lake bottom (DO_{BC}). In 2003 the range of DO_{BC} oscillations among five analysed lakes, seen as the rate of water oxygen saturation, amounted from 0% in Lake Ostrowite to 99% in Lake Nierybno (Fig. 1). The biggest oscillations of DO_{BC} were recorded in Lake Płęsno (0-83%) and Ostrowite (0-78%), and the lowest ones in the lakes: Wielkie Gacno (25-85%) and Nierybno (38-99%).

Various oxygen conditions in the studied lakes are confirmed by average percentage of water saturation with DO in the vertical distribution (DO_{MCV}). In 2003 the range of DO_{MCV} oscillations equalled from 22.5% (in Lake Płęsno at the end of the winter) to 101% (in Lake Wielkie Gacno in mid-spring). The biggest oscillations in the concentrations of DO_{MCV} were recorded in Lake Płęsno (22.5-97.6%) and Wielkie Krzywce (36.3-82.8%), and the smallest ones in Lake Wielkie Gacno (73.8-101%). The DO_{MCV} fluctuations resulted mainly from the changeability of the mean values of DO in the vertical distribution, which amounted from 1.0 to 11.9 $mg \cdot dm^{-3}$ in Lake Płęsno, from 4.9 to 10.9 $mg \cdot dm^{-3}$ in Lake Wielkie Krzywce, and from 8.5 to 12.4 $mg \cdot dm^{-3}$in Lake Wielkie Gacno. Various DO concentrations near the surface of some lakes are worth noting. In Lake Płęsno they amounted from 64 to 124%, which corresponded to the content of DO from 9.1 to 14.2 $mg \cdot dm^{-3}$, and in Lake Ostrowite from 74 to 100% (9.3-14.2 $mg \cdot dm^{-3}$).

The diversity in the concentration of DO in the vertical distribution made it possible to define oxygen gradients (DOG) in four seasons of the year (Tab. 2). The winter season proved most interesting with respect to this. It was at the end of the period with the ice over that the highest gradient in the surface layer of Lake Nierybno was ever recorded (10.1 $mg \cdot dm^{-3} \cdot m^{-1}$).

At the same time high DOG (5.1 $mg \cdot dm^{-3} \cdot m^{-1}$) was observed in another shallow lake - Wielkie Gacno. In the remaining lakes DOG revealed typical values, in the range of 2.3-2.6 $mg \cdot dm^{-3} \cdot m^{-1}$. Apart from the surface water layers in the lakes in the winter seasons, high DOG were also noted in deeper water layers at the end of summer stagnation periods: from 5.3 $mg \cdot dm^{-3} \cdot m^{-1}$ in Lake Płęsno from 1.3 $mg \cdot dm^{-3} \cdot m^{-1}$ in Lake Nierybno.

Total gradients of oxygen (DOG_T) were highest also at the end of the winter season and amounted from 0.4 $mg \cdot dm^{-3} \cdot m^{-1}$ (in the deepest of the studied lakes – Ostrowite) to 3.1 $mg \cdot dm^{-3} \cdot m^{-1}$ (in the shallowest lake – Wielkie Gacno). In the remaining seasons both DOG_T and other gradients were small and did not usually exceed 0.5 $mg \cdot dm^{-3} \cdot m^{-1}$ or stayed near 0.

The results of the examinations of the DO vertical distribution in the deepest places of the lakes at the end of the winter season and simultaneously near the ice break-up dates are worth looking at. This distribution is similar in the same lakes in various years despite slightly different values of DO concentrations at different depths. Most lakes are characterised by regular decline in DO concentration from the surface

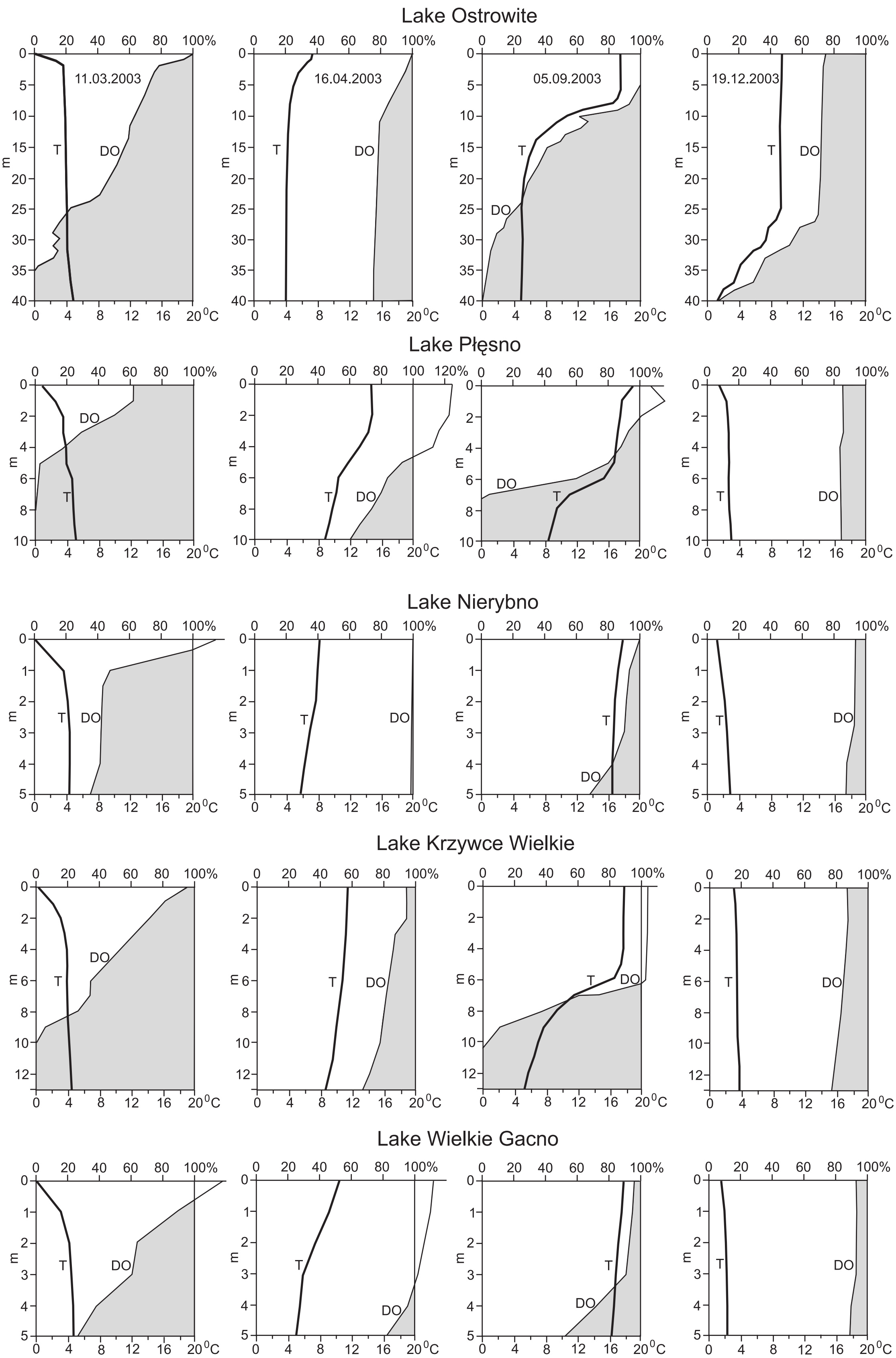

Fig. 1. Vertical distributions of dissolved oxygen (DO, in % of oxygen saturation of water) and water temperature (T, in °C) in different seasons of 2003.

Table 2. Oxygen gradients of the lakes (in mg·dm^{-3}·m^{-1}): DO_{MAX}-maximum, DO_S-surface (0-2 m), DOG_T-total (surface-bottom), (the depth of occurrence in parentheses).

DOG	Lake Nierybno	Lake Ostrowite	Lake Wielkie Gacno	Lake Płęsno	Lake Wielkie Krzywce
Winter. March 2003. Ice cover					
DO_{MAX}	10.1 (0-1 m)	2.3 (1-2 m)	5.1 (0-1 m)	2.5 (2-3 m)	2.6 (0-1 m)
DO_S (0-2 m)	5.4	2.1	4.5	1.4	2.1
DOG_T	2.5	0.4	3.1	1.0	1.0
Spring. April 2003.					
DO_{MAX}	0.1 (4-5 m)	0.4 (3-4 m)	1.3 (4-5 m)	1.4 (4-5 m)	0.5 (11-12 m)
DO_S (0-2 m)	0.0	0.0	0.0	0.0	0.0
DOG_T	0.0	0.1	0.5	0.6	0.2
Summer. August/September 2003.					
DO_{MAX}	1.3 (4-5 m)	2.4 (9-10 m)	1.9 (3-4 m)	5.3 (6-7 m)	3.5 (6-7 m)
DO_S (0-2 m)	0.4	0.0	0.0	0.1	0.0
DOG_T	0.6	0.2	0.5	1.0	0.8
Autumn. December 2003.					
DO_{MAX}	0.7 (3-4 m)	1.3 (32-33 m)	0.5 (3-4 m)	0.4 (0-1 m)	0.3 (10-11 m)
DO_S (0-2 m)	0.2	0.0	0.1	0.2	0.1
DOG_T	0.3	0.2	0.2	0.1	0.1

down to the bottom. However, the values of that decline vary. The biggest value was recorded in the shallow lake - Wielkie Gacno, and the lowest value was found in the deepest lake – Ostrowite (Fig. 2). Lake Nierybno represented another type. There, violent decline in DO occurred solely in the surface water layer, and the deeper layers were equally oxygenated. Only Lake Płęsno revealed diverse courses of the DO vertical distribution close to the ice break-up dates in the analysed years. It is worth underlining that due to violent declines in DO concentrations in most lakes there were severe oxygen deficits or shortages, typical of hypoxia and anoxia, in the deeper parts of the lake reservoirs.

Unfavourable oxygen conditions in the deeper lake layers were also observed at the end of summer stagnation periods, at the turn of August and September. This refers to both the deepest lakes and some shallow ones (among others Lake Główka). In the lakes: Zielone and Płęsno, the shortage of oxygen was noticeable already halfway to their maximum depth. As during the winter, these lakes revealed similar courses of the DO vertical distribution in the consecutive years (Fig. 3).

However, Lake Ostrowite for which the data have been available for 40 years is recognised in the best way. In 1966 it showed almost an even distribution of DO from the surface down to the bottom in the quantity of 8-9 mg·dm^{-3} (Fig. 3). This proves low trophic state of the lake, so typical of oligotrophy. In the subsequent years oxygen deficits got more and more severe, and in 1996 DO completely disappeared starting from 26 metre. In the following years the situation improved: in 2004 and 2005 anoxia was observed merely in the deepest place of the lake, below the depth of 38 metres (Fig. 3). The shape of the oxygen curve, typical of a positive heterograde, characteristic of a-mesotrophic lakes, is the most important property of Lake Ostrowite.

Discussion

The results presented in this study refer to the lakes which are located close to one another (the maximum distance amounts to merely 6 km), and in the forested area (forests cover from 80 to 95% of their catchment area). That area is not influenced by any major anthropogenic factors or threats. Moreover, these lakes are located in the upper part of the catchment and represent types of closed lakes, which makes their properties more advantageous. Despite this, very strong diversity in dissolved oxygen concentrations and in many cases hypoxia and anoxia were recorded. This has been endangering proper functioning of the discussed lake ecosystems. Moreover, eutrophication processes have developed strongly, though they have been undergoing in the conditions similar to the natural ones.

The profile of most oxygen curves is similar to a clinograde, typical of the conditions with oxygen deficits in deeper layers. Only Lake Ostrowite has a different one, corresponding to a positive heterograde.

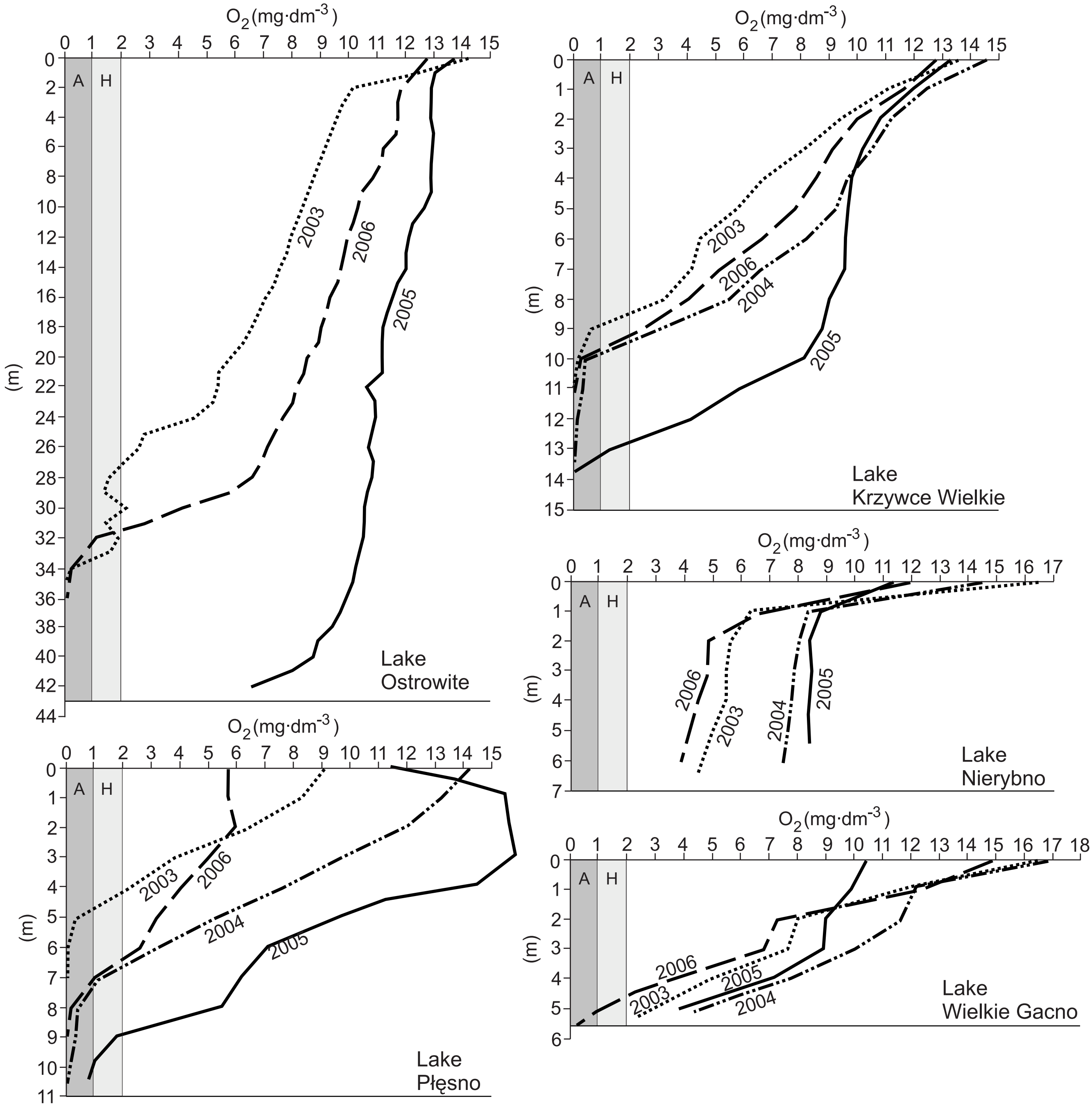

Fig.2. Vertical distribution of dissolved oxygen at the end of the periods with the ice cover. Symbols: A – anoxia; H – hypoxia.

It is worth noting that in 1960s the vertical distribution of oxygen was similar to an orthograde, which indicates existing oligotrophy then. In the subsequent years oxygen conditions deteriorated in Lake Ostrowite. Only at the beginning of the twenty-first century oxygen concentration increased, particularly in its deeper layers (compare Fig. 3).

Various concentrations of DO in the same lakes in different years during the periods with the ice cover are worth studying. In order to explain this phenomenon the authors examined the dependency between the mean concentration of DO in the vertical (from the surface to the bottom in the deepest place of the dimictic lakes) and the duration of the period since

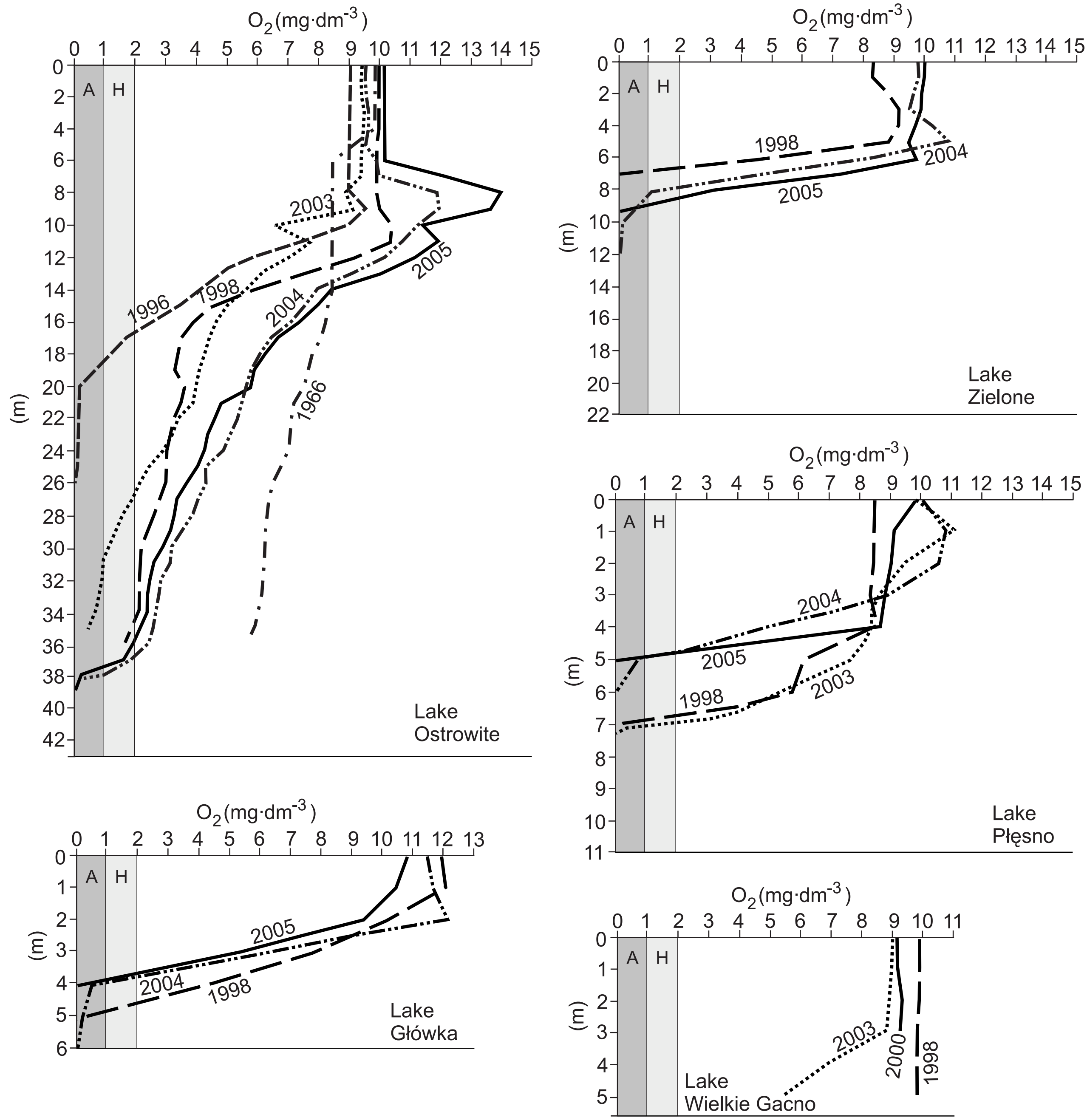

Fig.3. Vertical distribution of dissolved oxygen at the end of the periods of summer stagnation. Symbols: A – anoxia; H – hypoxia.

the ice cover formation on the lake till the measurement day. The determining coefficient $R^2 = 0.78$ (Fig. 4) indicates the existence of this dependency. This means that the duration of the period with the ice cover is an important factor which influences DO concentration in the lake vertical section.

The presented data lead to a conclusion that the vertical distributions of DO are particularly interesting at the end of winter, during the periods with the ice cover. The DO gradients found in Lake Nierybno at the end of winter 2003 (10.1 $mg \cdot dm^{-3} \cdot m^{-1}$) belong to the highest values, unique in the subject literature. This phenomenon may be related to dynamic processes of photosynthesis occurring just before the ice break-up dates. However, detailed explanation requires further research, not only thermal-oxygen but also chemical and biological examinations.

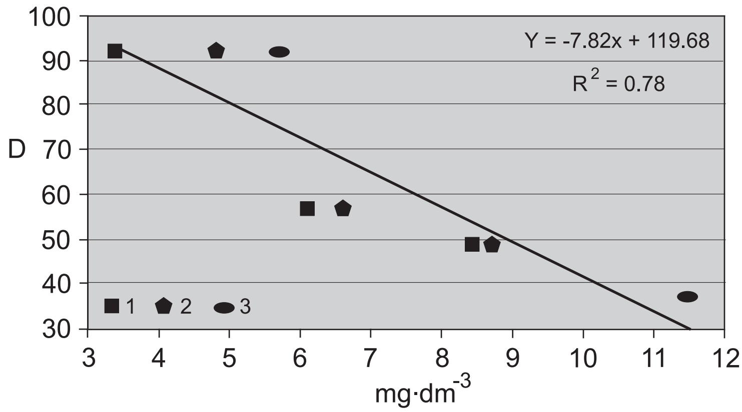

Fig. 4. Dependencies between the mean concentration of DO in the vertical distribution of the lakes (mg·dm^{-3}) and the duration of the ice cover (D, in days). Symbols: 1 – Lake Płęsno; 2 – Lake Wielkie Krzywce; 3 – Lake Ostrowite.

Final remarks

The investigation results obtained in the area of the "Bory Tucholskie" National Park documented substantial diversity of oxygen conditions, which in many cases must be considered unfavourable to lake ecosystems. Oxygen deficits and seasonal shortages even in shallow lakes are particularly dangerous.

Despite substantial diversity in DO concentrations in the studied lake group, the course of oxygen curves is very similar in the same lakes and in the same seasons in the consecutive years. This confirms strong individual properties of each of the studied lakes and provides the necessity to popularise such a type of research for other lakes located nearby.

The duration of periods without oxygen depends on atmospheric conditions. With more frequent extreme weather conditions we need to be ready to counteract to their negative consequences and oxygenate lakes from time to time (for instance, during long periods with the ice cover). The above remarks prove the necessity to conduct further and constant examinations not only in this area but also in other legally protected areas, regardless of the gravity of threat with anthropologic factors.

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Streszczenie

Niniejszą pracę przygotowano na podstawie wyników pomiarów koncentracji tlenu rozpuszczonego (DO) w zróżnicowanych pod względem morfometrycznym jeziorach Parku Narodowego „Bory Tucholskie" (tab. 1). Wyniki własnych badań zostały uzupełnione materiałami z lat 60. XX wieku (z Instytutu Rybactwa Śródlądowego w Olsztynie) oraz z końca lat 90. XX wieku (Jutrowska, Marszelewski 1998, Gwoździński et al. 2001). Dane dla kilku jezior z sezonów letnich udostępniła dr E. Nowicka. Stwierdzono duże zróżnicowanie stopnia nasycenia wody tlenem nad dnem (od 0 do 99%, ryc. 1), a także średniego nasycenia wody tlenem w profilu pionowym (od 22,5% pod koniec zimy w jeziorze Płęsno do 101% w środku wiosny w jeziorze Wielkie Gacno). Za najbardziej interesujący pod względem zróżnicowania warunków tlenowych uznano okres występowania pokrywy lodowej. Przy końcu tego okresu zanotowano rekordowo wysokie gradienty pionowego rozkładu tlenu, do 10.1 $mg \cdot dm^{-3} \cdot m^{-1}$ w jeziorze Nierybno (tab. 2). W okresie zimy najwięcej jezior charakteryzowało się równomiernym spadkiem DO od powierzchni do dna, który był największy w płytkim jeziorze Gacno Wielkie, a najmniejszy w głębokim jeziorze Ostrowite (ryc. 2). Niekorzystne warunki tlenowe występowały pod koniec okresów stagnacji letnich, zarówno w jeziorach najgłębszych jak i w niektórych jeziorach płytkich. W głębszych częściach mis jeziornych występowały silne deficyty tlenowe lub całkowity brak tlenu, typowe dla hypoxi i anoxi (ryc. 3). Kształt większości krzywych tlenowych zbliżony był do klinogrady. Jedynie w jeziorze Ostrowite odpowiadał heterogradzie dodatniej, chociaż jeszcze w latach 60. XX wieku był ortogradowy. Stwierdzono silną zależność między średnią koncentracją DO w pionie (od powierzchni do dna w najgłębszym miejscu jezior dymiktycznych), a długością okresu od dnia powstania pokrywy lodowej na jeziorze do dnia, w którym wykonano pomiar (R^2 = 0,78, ryc. 4). Oznacza to, że długość okresu z pokrywą lodową jest ważnym czynnikiem wpływającym na koncentrację DO w profilu pionowym jeziora.