Arch. Pol. Fish. (2012) 20: 39-50
DOI 10.2478/v10086-012-0005-3

RESEARCH ARTICLE

Thermal and oxygen conditions in lakes under restoration following the removal of herbivorous and seston-filtering fish

Agnieszka Napiórkowska-Krzebietke, Anna Szostek, Bożena Szczepkowska, Barbara Błocka

Received – 28 September 2011/Accepted – 03 February 2012. Published online: 31 March 2012; ©Inland Fisheries Institute in Olsztyn, Poland
Citation: Napiórkowska-Krzebietke A., Szostek A., Szczepkowska B., Błocka B. 2012 – Thermal and oxygen conditions in lakes under restoration following the removal of herbivorous and seston-filtering fish – Arch. Pol. Fish. 20: 39-50.

Abstract. The thermal and oxygen conditions were determined in lakes under restoration after the removal of herbivorous and seston-filtering fish. Studies of the thermal and oxygen conditions were conducted from March to November from 2000 to 2010, except in 2006, in lakes Dgał Wielki, Dgał Mały, and Warniak. The beginning of thermal stratification was usually observed in dimictic lakes in May, although this type of layering was noted several times by the end of April. Lake Dgał Mały has characteristics that are typical of so-called cold thermal lakes, while the characteristics of Dgał Wielki identify it as a thermally moderate lake. Oxygen depletion was observed in summer in the hypolimnion and metalimnion (clinograde curve) and H_2S occurred in the deepest water layers, which was noted in the 1950s; this indicates that this occurred prior to, during, and following the experimental introduction of fish. Oxygen maximums have been noted in the metalimnion sporadically (positive heterograde). The water masses in the polymictic Lake Warniak warmed most quickly in spring and summer and cooled in fall. Homothermia is usually noted in the growth season, with good oxygenation from the surface to the bottom with frequent occurrences of supersaturation, which could signal intense production processes. The studied lakes differed significantly in terms of water mass warming, oxygen content, and degree of staticity.

Keywords: air, lakes, oxygen, stratification, temperature, water

A. Napiórkowska-Krzebietke [✉]
Department of Hydrobiology
Inland Fisheries Institute in Olsztyn
Oczapowskiego 10, 10-719 Olsztyn, Poland
e-mail: akrzebietke@infish.com.pl

A. Szostek, B. Błocka
Department of Lake Fisheries in Giżycko
Inland Fisheries Institute in Olsztyn, Poland

B. Szczepkowska
Department of Sturgeon Fish Breeding in Pieczarki
Inland Fisheries Institute in Olsztyn, Poland

Introduction

Lakes Dgał Wielki, Dgał Mały, and Warniak were stocked with varying frequency in the 1960s, 1970s, and 1980s with the herbivorous and seston-filtering fish species of carp, *Cyprinus carpio* L.; grass carp, *Ctenopharyngodon idella* (Val.), silver carp, *Hypophthalmichthys molitrix* (Val.); and bighead carp, *Hypophthalmichthys nobilis* (Rich.), with the aim of testing the possibilities of maintaining an advantageous trophic status and to decelerate the progression of overgrowth (Ciepielewski 1985, Białokoz 1997, Zdanowski et al. 1999). The introduction of these fish led to significant changes in the occurrence and distribution of submerged vegetation which resulted in its near total disappearance for a period of nearly twenty years (Krzywosz 1997). Changes observed in the chemical composition of the waters and bottom sediments are evidence of increases in the production of the lakes (Krzywosz et al. 1980, Zdanowski et al. 1999). Intense exploitation, natural mortality, and winter oxygen depletion (1985, 1987, 1996) permitted limiting fish pressure substantially. Evidence of submerged vegetation regeneration was evident in 1987 in Lake Dgał Wielki, but not until 1993 in Lake Warniak with the domination in 2002 of charophytes (Bałdyga 2008, Hutorowicz and Dziedzic 2008), which stabilized the clean water status of the lake. When evaluating the reaction of lakes to pressure, parameters that characterize the intensity of matter cycling in the aquatic environment, which are expressed, among other ways, in the degree of water mixing (Patalas 1960a) and based on oxygen concentrations in the water column (Maślanka 1998), are extraordinarily useful. Oxygen conditions impact the equilibrium of lake ecosystems, and the content of dissolved oxygen in the water determines the course of biological and chemical processes that determine water quality (Ivanow et al. 2002). In turn, the thermal and oxygen regime of standing waters in the temperate geographic zone is largely dependent on air temperature and the reach of water mass mixing (Patalas 1960b, Hutchinson 1957, Ambrosetti and Barbanti 2001, Tórz et al. 2004).

Oxygen depletion in the hypolimnia of both deep lakes and even in the metalimnion (Dgał Mały) was noted both prior to and during experimental stocking as well as during periods of intense exploitation of these fish (Zachwieja 1972, Karpiński 1994, Tunowski 2008). The impact of introducing allochthonous fish on water quality, including the shaping of thermal and oxygen conditions, can either have significant (Rose 1972, Lembi et al. 1978) or insignificant (Shireman et al. 1985, Opuszyński and Shireman 1995, Kirkağaç and Demir 2006) consequences. The aim of the study was to describe the long-term variability in water temperature and oxygen content in three lakes under restoration following the removal of herbivorous and seston-filtering fish. The first evidence of this process was observed with the regeneration of submerged vegetation.

Study area and methods

Lakes Dgał Wielki, Dgał Mały, and Warniak are located in the mesoregion of the Great Masurian Lakeland (northeastern Poland), in the village of Pieczarki about 10 km north of Giżycko in the drainage basin of Lake Dargin. According to fisheries classification, these are cultured lakes within the framework of the Department of Sturgeon Fish Breeding of the Inland Fisheries Institute in Olsztyn. These lakes have surface areas of <100 ha, with differing maximum and mean depths, and are dimictic and polymictic (Table 1).

Table 1

Morphometric parameters of lakes Dgał Wielki, Dgał Mały, and Warniak

Parameters	Dgał Wielki	Dgał Mały	Warniak
Surface area (ha)	93.92	14.44	38.4
Maximal depth(m)	18.8	15.8	3.7
Mean depth (m)	5.7	4.6	1.2
Volume (x 103 m^3)	5401	618	456.7
Maximal length (m)	1275	670	1000
Maximal width (m)	1110	295	500
Length of shoreline (m)	4403	1620	2625
Shoreline development	1.28	1.28	1.20
Type of stratification	dimictic	dimictic	polimictic

The largest of the studied lakes is Dgał Wielki, which is of a regular shape, and its low index of shoreline development (1.28) means it is nearly circular (Hutchinson 1957). In the eastern part of the lake there are two small, shallow bays the muddy bottoms of which are covered with a layer of organic sediments that are covered to a small degree with emerged vegetation comprising primarily *Phragmites australis* (Cav.) Trin. ex Steud and *Acorus calamus* L. In the northern part, just beyond the island is a third bay with a moderately hard, sandy and sandy-gravel bottom with a small quantity of organic sediments. The lake is surrounded by small hills, but it adjoins a flat valley on the northwest side. In the southern part of the lake, where distinct deepening of the bottom is visible, there is a rather narrow, interrupted strip of emerged vegetation in the littoral zone along the shore that is overgrown with a tall, dense coniferous forest. Dgał Wielki is a flow through lake with inflow from Lake Warniak in the northern part and outflow to Lake Dgał Mały in the northeast.

The second largest of the lakes is Warniak, which is very shallow and also has a minimally developed shoreline. Emerged vegetation comprises a quite wide and dense shoreline strip that covers nearly the entire shoreline of the lake. The dominant species here is *P. australis*, with the co-dominants of *Typha latifolia* L., *Schoenoplectus lacustris* (L.) Palla, and *A. calamus*. The lake basin is filled with a great quantity of residual limestone sediment (Stangenberg 1938), which even reaches the littoral zone. A field drainage canal flows into the lake and there is an outflow into Lake Dgał Wielki. The lake is surrounded by gently sloping, forested hills and in the region of the inflow and outflow there are swampy meadows. According to limnological typology, or classification, (Stangenberg 1936) Lake Warniak is eutrophic and is close to being a natural pond, while according to Wiszniewski (1953) this lake is a polymictic or epilimnetic basin in terms of its staticity.

Lake Dgał Mały has the smallest surface area of the three lakes. Its basin shape is regular with a deep located near the center. The lake bottom is generally muddy, and only in a few areas on the eastern and western shores is the bottom harder. Since the side of the lake basin slope sharply, it has a very narrow littoral zone with small stands of emerged vegetation mostly comprising *P. australis*. According to the Stangenberg (1936) classification, Dgał Mały is eutrophic at an advanced stage of aging. The lake is located in a fairly deep valley, and its shores are covered with coniferous forests. There are swampy areas at the lake inflow and outflow sites. The location and small surface area limits the mixing of this lake's water masses. Waters from Lake Dgał Wielki flow into the lake and flow out of it into Lake Dargin.

Herbivorous and seston-filtering fish species, which included mainly grass carp, bighead carp, and silver carp, were stocked in all three lakes. The experiment was initiated in 1966 in Lake Dgał Wielki, and then continued in the other two lakes in the 1970-1978 and 1984-1985 periods (Karpiński 1994, Krzywosz et al. 1980, Krzywosz 1997, Tunowski 2005, 2006, 2008). Fish catches were begun shortly after the fish had been introduced. According to Krzywosz et al. (1980) and Krzywosz (1997), catches of grass carp in Lake Dgał Wielki in the 1970-1995 period ranged in quantity from 1 to 341 kg annually, while in Lake Warniak catches were from 4 to 696 kg annually. Fish biomass also decreased successively as a consequence of winter oxygen deficits and natural mortality, and from 1984 (Dgał Wielki) and 1990 (Warniak) only a few specimens of grass carp were noted (Krzywosz 1997, Zdanowski et al. 1999). The situations with regard to silver carp and bighead carp were analogous, and dramatic reductions in these seston-filtering fish were noted at the end of the 1990s (Zdanowski et al. 1999, Tunowski 2005, 2006).

The basis for the paper is thermal and oxygen data and air temperature data from the 2000-2010 period which were obtained through studies conducted by the Department of Lake Fisheries in Giżycko and the Department of Sturgeon Fish Breeding in Pieczarki of the Inland Fisheries Institute in Olsztyn, respectively. Water temperature and oxygen concentration measurements were taken in the pelagic zones of the lakes studied monthly during the growth season (from the moment ice cover melted until the lakes froze) in the 2000-2010 period, except in 2006. These parameters were measured every 1 m in the deepest part of the lake using an OxyGuard Handy probe with an accuracy of ± 0.2°C. The atmospheric air temperature was measured (to the nearest 0.1°C) in a weather station deployed at a height of 2 m above the ground and equipped with a mercury meteorological thermometer. Readings were taken three times daily at 07:00, 13:00, and 19:00 (standard time) and at 08:00, 13:00, and 20:00 (daylight savings time). The mean daily, decadal, monthly, and annual temperatures were calculated using these data.

Significant changes in layer thickness, temperature, and dissolved oxygen content in lakes Dgał Wielki and Dgał Mały were tested with the Mann-Whitney U test, which is used to compare two independent samples (groups) (Łomnicki 2002). The level of significance was 0.05. The Statistica package (StatSoft, Inc.) was used for statistical analysis.

Results

The mean surface layer water temperature in the lakes from the ten years of studies was the lowest just after the ice cover had melted, which was usually in March (Fig. 1a). The maximum values were noted in July (approximately 22.5°C). The highest temperature values tended to be observed in spring and summer at 0.5-19.0°C and 17.0-26.0°C, respectively, in the polymictic Lake Warniak, with maximum values noted in July of 2001 and 2010. However, the lowest values were systematically noted in this lake from 2.0 to 18.2°C in fall. The dimictic Lake Dgał Wielki was characterized by the lowest mean temperature in the surface layer from March to July, and the highest from August to the end of the growth season. The temperature range in this lake during the spring months was 0.7-18.0°C, in summer – 17.0-26.0°C, and fall – 4.0-19.2 C. The water temperature values in Lake Dgał Mały were intermediate, although the range of temperatures of the surface layer in this lake were comparable to those in Lake Dgał Wielki. In spring the range was 0.2-18.2°C, in summer – 17.0-25.0°C, and in fall – 4.0-18.8°C. The course of fluctuations in surface layer water temperature values in the studied lakes was similar to the mean daily air temperature during the period from March to November in the 2000-2010 period (Fig. 1b).

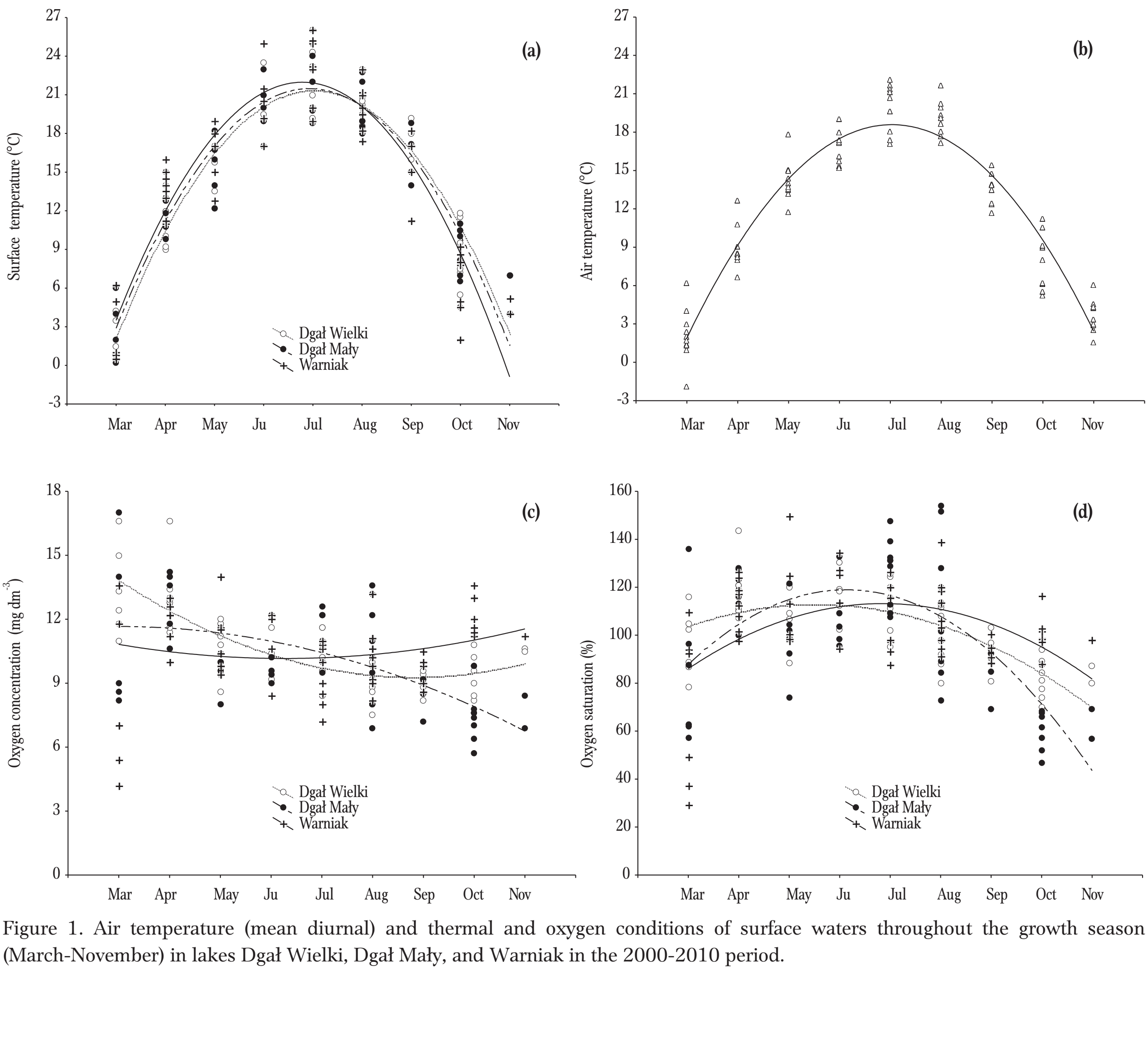

Figure 1. Air temperature (mean diurnal) and thermal and oxygen conditions of surface waters throughout the growth season (March-November) in lakes Dgał Wielki, Dgał Mały, and Warniak in the 2000-2010 period.

The mean values of oxygen content in the surface water layer of the lakes fluctuated quite considerably throughout the season. The lowest concentrations of this gas (approximately 5.0 mg O_2 dm^{-3} and 35% saturation) were confirmed in spring in Lake Warniak immediately after the ice cover melted (Fig. 1c, 1d). However, the highest values were noted in lakes Dgał Wielki and Dgał Mały in March at approximately 17.0 mg O_2 dm^{-3}.

The data indicate that during the vegetation season in the 2000-2010 period the mean water temperature from the surface to the bottom was 9.4 °C in Lake Dgał Wielki (Fig. 2a), 7.7°C in Dgał Mały (Fig. 2b), and 14.4°C in Lake Warniak, (Fig. 2c) at a mean daily air temperature of 11.7°C (Fig. 2d). The warmest water masses in the lakes (with means higher than that for the decade) were confirmed in 2002, 2007, and 2008, but the coolest (with means lower than that for the decade) were noted in 2003, 2009, and 2010 in Lake Dgał Wielki and in 2003, 2004, and 2009 in lakes Dgał Mały and Warniak (Fig. 2). The greatest amplitude in deviations from growth season mean temperatures was noted in the polymictic Lake Warniak. The daily mean air temperatures in individual years were higher than those noted in the stratified lakes; however, the trends they exhibited were similar throughout the decade studied (Fig. 2d).

The dissolved oxygen content noted throughout the water column of the stratified lakes during the decade studied ranged from 0 to 17.0 mg dm^{-3}, while in the polymictic lake the range was from

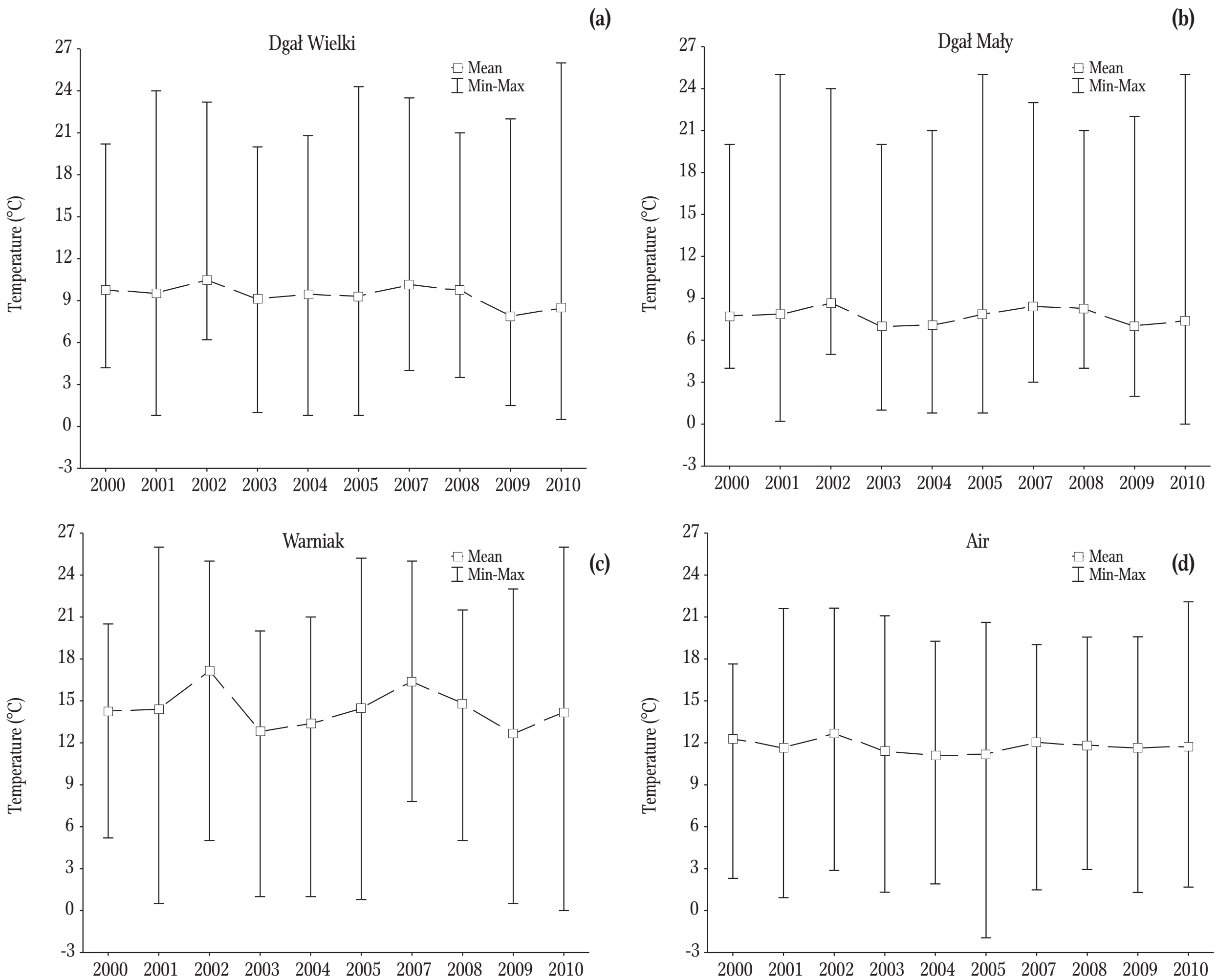

Figure 2. Air temperature and water temperature of lakes Dgał Wielki, Dgał Mały, and Warniak (mean, minimal, and maximal values for entire growth season) in the 2000-2010 period.

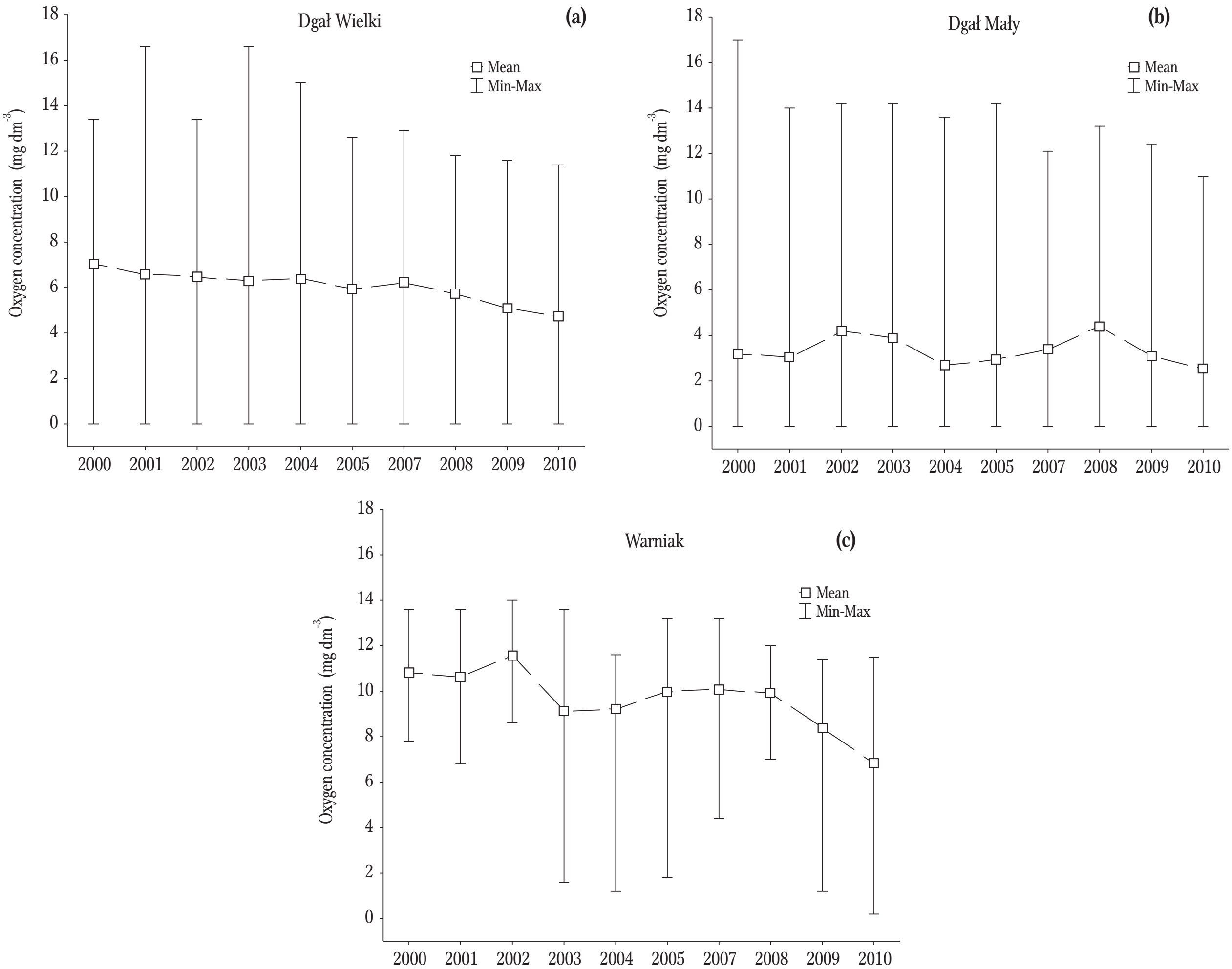

Figure 3. Oxygen concentration in lakes Dgał Wielki, Dgał Mały, and Warniak (mean, minimal and maximal values for entire growth season) in the 2000-2010 period.

approximately 0.2 to 14.0 mg dm^{-3} (Fig. 3). The long-term mean dissolved oxygen contents in the lake waters during the growth season were 6.1 mg dm^{-3} in lakes Dgał Wielki and 3.4 mg dm^{-3} in Dgał Mały, and 9.7 mg dm^{-3} in Lake Warniak. The mean values of dissolved oxygen concentration were usually higher than the long-term mean in the 2000-2007 period, but from 2008 there was a tendency for the mean values to be much lower than the long-term mean with a maximum of approximately 3.0 mg dm^{-3} in Lake Warniak.

Throughout the ten-year study period, the beginning of thermal stratification in the two dimictic lakes was usually noted in May, but this characteristic layering was noted several times at the end of April. The summer stagnation period usually persisted until the end of September, and during this period differences were confirmed in layer thickness. The euphotic layer, or epilimnion, in Lake Dgał Wielki reached an average depth of 5 m (Fig. 4a), and from 6 to 8 m in August. However, the epilimnion in Lake Dgał Mały was statistically significantly thinner ($U = 120$; $n = 68$; $P = 0.000$) and only reached depths of about 2 m, and from 2 to 5 m in August. The thickness of the metalimnion in both lakes was an average of 4 m (Fig. 4b). The hypolimnion, or stagnant water layer, was usually at depths of 10 m in Lake Dgał Wielki and 7 m in Lake Dgał Mały (Fig. 4c), and the thickness in both lakes was similar (Fig. 4d).

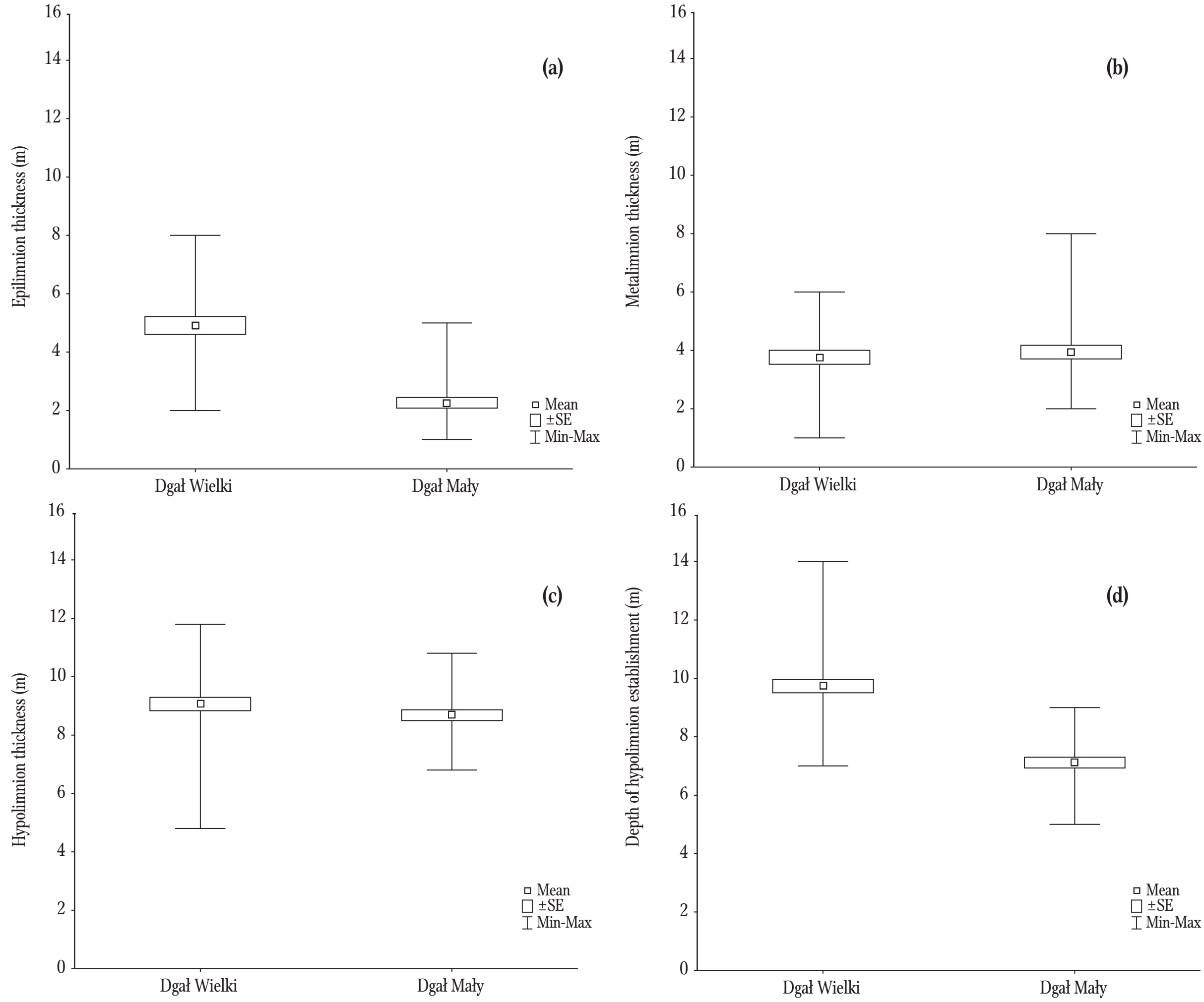

Figure 4. Epilimnion, metalimnion, and hypolimnion thickness and hypolimnion depth in lakes Dgał Wielki and Dgał Mały during summer stagnation in the 2000-2010 period.

The greatest water warming was noted in the epilimnion waters mostly in July. The range and mean temperatures of these water layers were very similar in both of the stratified lakes (Fig. 5a). The mean temperature in the Lake Dgał Wielki metalimnion was approximately 12.3°C (Fig 5b), and 6.5°C in the hypolimnion (Fig. 5c). Meanwhile, statistically significantly lower mean values were confirmed in both layers in Lake Dgał Mały at 11.1°C (U = 412; n = 68; P = 0.042) and 4.7°C (U = 83; n = 68; P = 0.000), respectively.

The mean dissolved oxygen content in the epilimnion ranged from 6.9 to 11.6 mg dm^{-3} in Lake Dgał Wielki and from 5.1 to 13.5 mg dm^{-3} in Lake Dgał Mały (Fig. 5d). Oxygen saturation was noted frequently in the water surface layer with a maximum of 151%. Oxygen concentration in the metalimnia of the two lakes differed substantially (U = 357.5; n = 68; P = 0.007), with means of 3.4 mg dm^{-3} in Lake Dgał Wielki and 1.8 mg dm^{-3} in Lake Dgał Mały (Fig. 5e), which correspond to 42 and 27% saturation, respectively. Exceptionally in July in 2005 and 2009 in Lake Dgał Mały and in 2010 in Lake Dgał Wielki the oxygen maximum was noted in the metalimnion (positive heterograde). Throughout the entire study period from 2000 to 2010, oxygen deficits (clinograde curve) in the hypolimnion and even in the metalimnion and the occurrence of H_2S in the deepest water layers were noted in the summer. The water layer that was totally devoid of

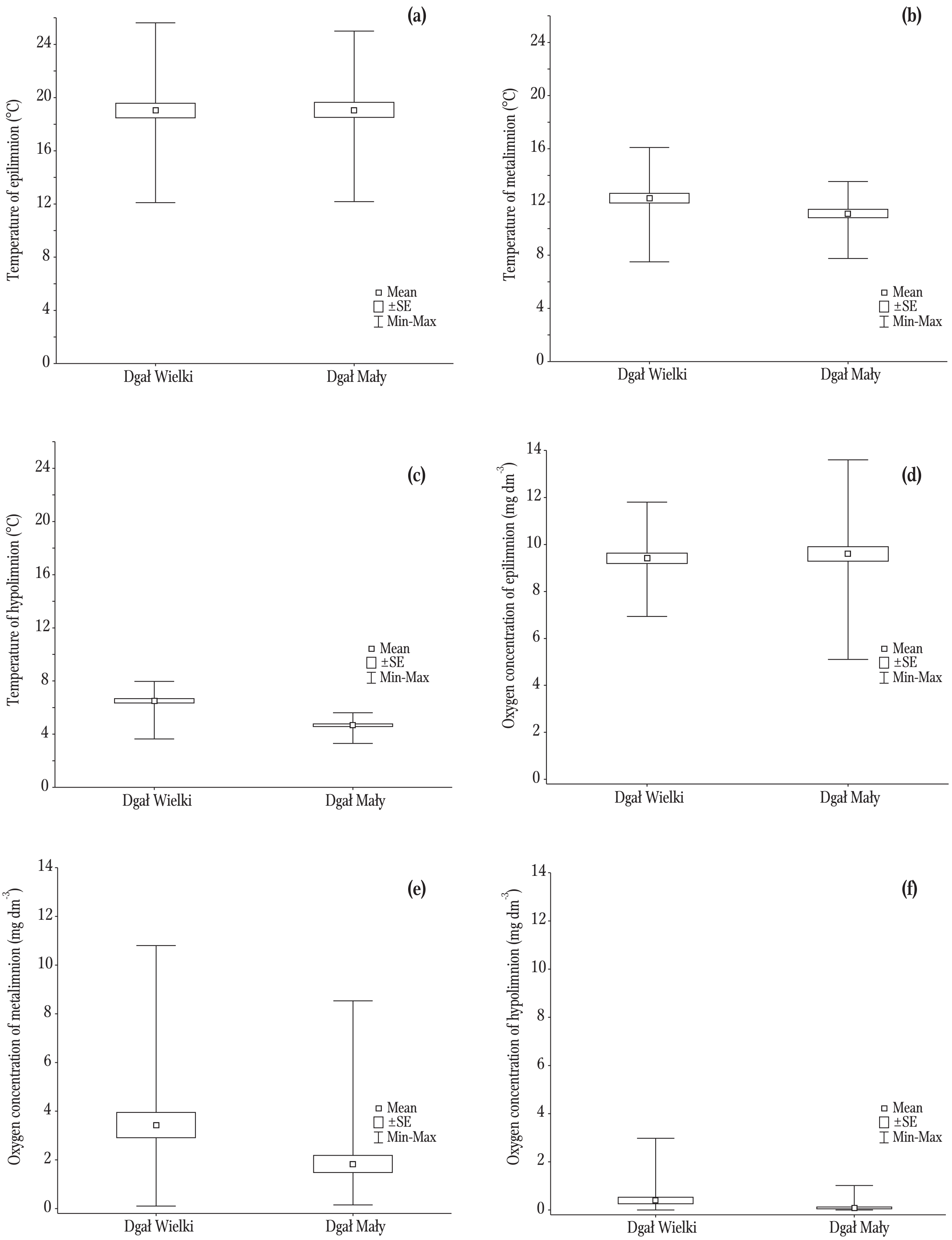

Figure 5. Temperature and oxygen concentration in the epilimnion, metalimnion, and hypolimnion of lakes Dgał Wielki and Dgał Mały during summer stagnation in the 2000-2010 period.

oxygen extended from a depth of 7 m to the bottom in the deepest lake and from 4 m downward in the more shallow lake in July and August. Only in Lake Dgał Wielki was oxygen confirmed throughout the water column each spring and fall. Frequent oxygen deficits of less 1.0 mg dm^{-3} were noted in the near-bottom layers of Lake Dgał Mały throughout the growth season (Fig. 5f).

Discussion

Lakes Dgał Wielki, Dgał Mały, and Warniak were subjected to experimental stocking mainly with herbivorous fish species from the 1960s to the 1980s. This was a certain type of biomanipulation that did not fulfill the anticipated role of curbing the effects of eutrophication as was evidenced by changes in the chemical composition of both waters and bottom sediments that signaled the lakes' increased production (Krzywosz et al. 1980, Zdanowski et al. 1999). Changes were also noted in the occurrence and distribution of submerged vegetation, which included its complete disappearance for a period of more than a decade (Krzywosz 1997), and which, after fish stocking was stopped, began to regenerate and stabilized the clean water status and facilitated the exchange of nutrients between the water column and the bottom sediments. Vegetation species that had not been observed previously appeared in Lake Warniak, and these were dominated by charophytes in 2002 (Bałdyga 2008, Hutorowicz and Dziedzic 2008).

The thermal regimes of the studied lakes depend on the micro-climates prevailing in given locations and the substantial, long-term variations in climatic factors, mainly atmospheric air temperature. Early summer layering was noted in both of the stratified lakes; this occurred several times at the end of April. While thermal layering is observed in some lakes in April, this occurs in most lakes in the Masurian Lakeland in May (Olszewski 1959, Napiórkowska--Krzebietke 2004). Such early stratification was a consequence of the occurrence of a shallow epilimnion and a cool hypolimnion. According to Olszewski (1959), this is characteristic of the bradymixing of various intensities linked to water circulation stagnation. Substantial differences in the extent of layer formation in the two lakes are related to differences in morphometry and the topography of the surrounding terrain, e.g., Lake Dgał Mały is located in a deep valley overgrown with forests. However, differences in layer thickness could probably be impacted by wind. Similar layer thicknesses and reaches in the two lakes were noted during study period in 1956-1969 and 1984-1989 (Zachwieja 1972, Karpiński 1994). That maximum surface water temperatures are usually noted in July was confirmed in the 1950s (Zachwieja 1972), which is also noted in other lakes (Zachwieja 1975, Kubiak and Tórz 2006, Naumenko et al. 2007).

Differing degrees of mixing had a significant impact on thermal differentiation. Since the extent of the thermocline included the layer just above the mean depth and the near-bottom water temperature in summer (under or sporadically equal to 5.0°C), Lake Dgał Mały has traits typical of so-called cool thermal lakes (Bernatowicz 1981). However, the thermal conditions in Dgał Wielki indicate it is a moderate thermal type lake, which the majority of Polish lakes are.

The thermal differentiation in the two stratified lakes is also reflected in their oxygen conditions. The surface layers of these lakes were supersaturated with oxygen, which can be a consequence of potential planktonic algal blooms and evidence of greater degrees of water eutrophication. The oxygen maximums in the metalimnion confirmed exceptionally in 2005, 2009, and 2010 are often observed in both mesotrophic and eutrophic lakes (Grochowska and Tandyrak 2006, Hutorowicz and Napiórkowska--Krzebietke 2008, Zdanowski et al. 2008). Anaerobic conditions, or anoxia phenomena, occurred in both lakes in the hypolimnion and even in the thermocline layer (clinograde curve). Similar oxygen conditions were noted beginning in 1956 prior to lake stocking and these persisted throughout the experimental period (1966-1985), and during intense catches of these fish (Zachwieja 1972, Karpiński

1994, Tunowski 2008). Anoxia in Lake Dgał Wielki was seasonal, while in Lake Dgał Mały it was permanent in most of the years studied. According to Zachwieja (1972), anoxia in the hypolimnion was noted in the former lake mainly in July and August and sporadically in June and September, while in the latter it was noted from March to the end of September. The occurrence of oxygen-depleted metalimnia and hypolimnia is noted widely in eutrophic stratified lakes around the world (Aberg and Rodhe 1942, Watts et al. 2001, Ivanow et al. 2002), including those in Poland (Zdanowski et al. 1984, Grochowska and Tandyrak 2006). Studies in the 1970s of the impact stocking herbivorous fish, mainly grass carp, had on water quality suggested increased concentrations of nutrients in waters and decreases in dissolved oxygen content (e.g., Rose 1972, Lembi et al. 1978). However, the results of studies in subsequent years did not confirm these finding unequivocally, and it was even suggested that temperature and oxygen values were not seriously altered following the introduction of grass carp (Opuszyński and Shireman 1995, Kirkağaç and Demir 2006).

The water masses warmed most quickly in the spring and summer and cooled most quickly in the fall in the shallow, polymictic Lake Warniak. The greater loss of warmth beginning in August could be linked to the greater degree of evaporation in this lake rather than in the others (Watts et al. 2001). Homothermia was also noted here most frequently throughout the growth season, as it was in the 1956-1969 period (Zachwieja 1972). This was accompanied by good oxygenation from the surface to the bottom, but with frequent periods of supersaturation, which could have indicated intense production processes. Beginning in 2000, no anoxic conditions were observed during the growth season, although oxygen deficits were observed several times during periods of prolonged ice cover with a layer of snow in the 1950s and also in the 1980s and 1990s (Zachwieja 1972, Karpiński 1994, Zdanowski et al. 1999). The phenomenon of hypoxia (< 50% oxygenation) of the near-bottom layer in Lake Warniak was only noted in 2010 when the ice cover melted, and it was much lower than 1.0 mg O_2 dm^{-3}, which suggests that it was possible that anoxic conditions occurred in the winter.

The lakes studied not only exhibited differences in thermal and oxygen conditions, but also with regard to the degree of staticity. According to Patalas (1960a), the unstratified Lake Warniak is an example of II degree staticity, where the theoretical possibility of mixing (4.4 m) only slightly exceeds the maximum depth, and processes of production and decomposition occur in the same layer. The stratified lakes Dgał Wielki and Dgał Mały are classified at III degree staticity as the reach of the epilimnion is at least 6 m in August, or as IV degree staticity when the epilimnion is most often 3-5 m thick. The relatively large reach of the epilimnion in Lake Dgał Wielki probably ensures the mineralization of a large quantity of organic substances in the epilimnion and the rapid return of nutrients to production, while the lesser reach of it in Lake Dgał Mały presents conditions under which there is a slight degree of mineralization in the epilimnion. In the 2000-2010 period, thermal and oxygen conditions of the studied lakes did not differ essentially from those prevailing prior to and during stocking or during catches of herbivorous and seston-filtering fish.

Acknowledgments. The material was collected as part of statutory research performed at the departments of Lake Fisheries in Giżycko and Sturgeon Fish Breeding in Pieczarki of the Inland Fisheries Institute in Olsztyn.

Author contributions. A.N.-K. developed the research concept; A.S., B.B. and B.S. performed field studies; A.N.-K. and A.S. analyzed materials; A.N.-K. wrote the text; B.S. made a critical review of the text.

References

Aberg B., Rodhe W. 1942 – Uber die Milieufaktoren in einigen südschwedischen Seen – Symb. Bot. Upsal. 5: 1-256 (in German).

Ambrosetti W., Barbanti L. 2001 – Temperature, heat content, mixing and stability in Lake Orta: a pluriannual investigation – J. Limnol. 60: 60-68.

Bałdyga E. 2008 – Dynamics of submerged macrophytes in Lake Warniak – PhD thesis, Olsztyn, 86 p. (in Polish).

Bernatowicz S. 1981 – Thermal types of lakes in north-eastern Poland – Ekol. Pol. 29: 585-594.

Białokoz W. 1997 – Intensity and effectiveness of feeding by selected fish species – Arch. Pol. Fish. 5: 5-36 (in Polish).

Ciepielewski W. 1985 – Experimentally increased fish stock in the pond type lake Warniak (Poland). Changes of ichthyofauna between 1970 and 1983 – Ekol. Pol. 33: 37-59.

Grochowska J., Tandyrak R. 2006 – Temperature and dissolved oxygen profiles in Lake Pluszne – Limnol. Rev. 6: 117-122.

Hutchinson G.E. 1957 – A Treatise on Limnology. Vol. I. Geography, physics and chemistry – Chapman and Hall, Ltd., London: 1-885.

Hutorowicz A., Dziedzic J. 2008 – Long-term changes in macrophyte vegetation after reduction of fish stock in a shallow lake – Aquat. Bot. 88: 265-272.

Hutorowicz A., Napiórkowska-Krzebietke A. 2008 – Phytoplankton assemblages in Lake Hańcza – In: Environment and ichthyofauna of Lake Hańcza (Eds) J. Kozłowski, P. Poczyczyński, and B. Zdanowski, Wyd. IRS Olsztyn: 93-102 (in Polish).

Ivanow V.A., Lyubartseva S.P., Mikhailova É.N., Shapiro N.B., Shteinman B.S. 2002 – Modeling of thermal and oxygen conditions in lake Kinneret (Israel) – Phys. Oceanogr. 12: 43-53.

Karpiński A. 1994 – The changes of phosphorus concentration in water and bottom sediments of three eutrophic lakes – PhD thesis, Olsztyn, 72 p. (in Polish).

Kirkağaç M.U., Demir N. 2006 – The effects of grass carp (*Ctenopharyngodon idella* Val., 1844) on water quality, plankton, macrophytes and benthic macroinvertebrates in a Spring pond – Turk. J. Fish. Aquat. Sci. 6: 7-15.

Krzywosz T. 1997 – The effect of grass carp (*Ctenopharyngodon idella* Valenciennes, 1844) on the environment of selected lakes – Arch. Pol. Fish. 5: 5-38 (in Polish).

Krzywosz T., Krzywosz W., Radziej J. 1980 – The effect of grass carp (*Ctenopharyngodon idella* Val.) on aquatic vegetation and ichthyofauna of Lake Dgal Wielki – Ekol. Pol. 28: 433-450.

Kubiak J., Tórz A. 2006 – Thermal regime of the biggest dimictic lakes of Western Pomerania region – Limnol. Rev. 6: 155-162.

Lembi C.A., Ritenour B.G., Iverson E.M., Forss E.C. 1978 –The effects of vegetation removal by grass carp on water chemistry and phytoplankton in Indian ponds – Trans. Am. Fish. Soc. 107: 161-171.

Łomnicki A. 2002 – Introduction to statistics for naturalists – PWN, Warszawa, 263 p. (in Polish).

Maślanka W. 1998 – The oxygen content differentiation in the water of selected lakes in the Pomeranian Lakeland as a measure of their degradative transformations – In: Degradative threats and protection of lakes, Bad. Limnol. 1: 193-202 (in Polish).

Napiórkowska-Krzebietke A. 2004 – Long-term changes of phytoplankton in lakes Niegocin, Mamry Północne and Kirsajty – PhD thesis, Olsztyn, 141 p. (in Polish).

Naumenko M., Karetnikov S., Guzivaty V. 2007 – Thermal regime of Lake Ladoga as a typical dimictic lake – Limnol. Rev. 7: 63-70.

Olszewski P. 1959 – The intensity levels of a wind impact on lakes – Zesz. Nauk. WSR Olsztyn, 4: 111-132 (in Polish).

Opuszyński K., Shireman J.V. 1995 – Herbivorous fishes: culture and use for weed management – CRC Press, Boca Raton, Florida, 223 p.

Patalas K. 1960a – Mixing of water as the factor defining intensity of food materials circulation in morphologically different lakes of Węgorzewo district – Roczn. Nauk. Rol. 77-B-1: 223-240 (in Polish).

Patalas K. 1960b – Thermal and oxygen conditions and transparency of water in 44 lakes of Węgorzewo district – Roczn. Nauk. Rol. 77-B-1: 105-209 (in Polish).

Rose S. 1972 – What about the white amur? A superfish or a supercurse? – Florida Naturalist: 156-157.

Shireman J.V., Hoyer M.V., Maceina M.J., Canfield D.E. 1985 – The water quality and fishery of Lake Baldwin, Florida: 4 years after macrophyte removal by grass carp – Integrated Approaches to Lake Management: 201-206.

Stangenberg M. 1936 – Limnological outline against hydrological ratios of the Suwałki Lakeland – Rozpr. Spraw. Inst. Bad. Lasów Państw. 19: 1-85 (in Polish).

Stangenberg M. 1938. Chemical composition of deep-sea sediments of Suwałki lakes – Rozpr. Spraw. Inst. Bad. Lasów Państw. 31: 44 p. (in Polish).

Tórz A., Kubiak J., Nędzarek A. 2004 – Characteristics of selected hydrochemical factors of Lake Ińsko in years 1982-2002 – In: Lakes and artificial water reservoirs – functioning, revitalization and protection (Eds) A.T. Jankowski, and M. Rzętała, University of Silesia, Sosnowiec: 215-224 (in Polish).

Tunowski J. 2005 – The impact of a large stock of bighead and silver carp on zooplankton in dimictic Lake Dgał Mały – Komun. Ryb. 4: 16-24 (in Polish).

Tunowski J. 2006 – The changes in structure and abundance of zooplankton under the influence of a large stock of bighead and silver carp in polymictic Lake Warniak – Komun. Ryb. 1: 7-14 (in Polish).

Tunowski J. 2008 – The changes of zooplankton induced by fish pressure in chosen eutrophic lakes – In: The application of statistical methods in science research III – StatSoft Polska, Kraków: 393-404 (in Polish).

Watts J.M., Swan B.K., Tiffany M.A., Hurlbert S.H. 2001 – Thermal, mixing and oxygen regimes of the Salton Sea, California, 1997-1999 – Hydrobiologia 466: 159-176.

Wiszniewski J. 1953 – Comments regarding typology of Polish lakes – Pol. Arch. Hydrobiol. 1(14): 11-23 (in Polish).

Zachwieja J. 1972 – Long-term changes of physical-chemical properties of water in lakes under meteorological conditions – PhD thesis, Olsztyn, 50 p. (in Polish).

Zachwieja J. 1975 – Seasonal and several years' fluctuations of temperature, oxygen content and water visibility in the Mamry Lake complex – Ekol. Pol. 23: 587-601.

Zdanowski B., Korycka A., Zachwieja J. 1984 – Thermal and oxygen conditions and the chemical composition of the Great Masurian Lakes – Ekol. Pol. 32: 651-677.

Zdanowski B., Hutorowicz A., Tunowski J., Świątecki A., Olejnik G., Krzywosz T., Białokoz W., Chybowski Ł., Krzywosz W., Błocka B., Hutorowicz J., Robak A., Prusik S., Koprowska L., Ciemiński J., Węgleńska T., Lewandowski K., Jurkiewicz-Karnkowska E. 1999 – Ecological effects of long-term pressure of phytophagous and seston-feeding fish on the structure and functioning of the shallow Lake Warniak (Mazurian Lakeland, Poland) – Acta Hydrobiol. 41: 29-47.

Zdanowski B., Stawecki K., Pyka J.P. 2008 – Abiotic environment of Lake Hańcza – In: Environment and ichtyofauna of Lake Hańcza (Eds) J. Kozłowski, P. Poczyczyński, and B. Zdanowski, Wyd. IRS Olsztyn: 59-73 (in Polish).