

Seasonal changes of environmental conditions in the phytolittoral zone of Lake Ostrowite in the Bory Tucholskie National Park

Małgorzata Chobot*, Krzysztof Banaś**

*University of Gdańsk, Department of Oceanography and Geography, Piłsudskiego Av. 46, 81-378 Gdynia, Poland; e-mail: mch@ocean.univ.gda.pl

** University of Gdańsk, Department of Plant Ecology, Legionów 9, 80-441 Gdańsk, Poland; e-mail: dokkrb@ug.gda.pl

Abstract: The environmental conditions of submerged vegetation in Lake Ostrowite (the Bory Tucholskie National Park) were examined at monthly intervals from July 2004 to December 2006. The seasonal variability of environmental features was determined based on 3-5 water and sediment samples collected each time in the central part of the aquatic plant population's home range (4-5 m deep). The following properties were measured in the water: pH, conductivity, redox, colour and concentrations of Ca, CO₂, HCO₃⁻, CO₃²⁻ and humic acids (HA). Apart from pH, conductivity, redox and Ca content, hydration and organic matter content were determined in the sediment. The analysis of variance showed that conductivity, concentrations of HCO₃⁻ and humic acids and colour are constant in the water, while in the sediment all the studied features except pH. It is worth mentioning that in spring water redox was very changeable (-178-110 mV), whereas in the sediment it was always negative (-140 ±86 mV). In summer water (7.65-8.28) and sediment (6.92-7.91) pH was higher than in spring (p<0.001). The remaining properties were almost the same as in spring and did not show statistically significant differences. In autumn variations were recorded only in the water: pH (7.30-7.57; p<0.001) and CO₂ concentration (8 ±1 mg l⁻¹; p=0.044) were lower than in summer, while redox (179 ±1 mV; p=0.004) and Ca concentration (41.9 ±0.8 mg l⁻¹; p = 0.020) were higher. In winter only water pH was lower than in summer (7.50-7.60; p=0.001), and the remaining features did not exhibit any variations in relation to the other seasons. The low variability of the aquatic environment features of Lake Ostrowite guarantees favourable conditions for the growth and development of submerged plants. On the other hand, well-developed submerged vegetation dominated by stoneworts maintains the stability of the conditions in the lake.

Key words: hard water lake, environmental conditions, seasonal variability, stoneworts

Introduction

The environmental conditions in water bodies are constantly changed by various natural and human-induced factors. The features of the physico-geographical environment of the catchment area, as well as the morphometric parameters of the water body and its hydrological regime, accelerate or block the supply of organic matter to the lake, which affects its trophic level, water pH and hardness, its electrolytic conductivity and colouring, light and oxygen availability, and consequently plant species diversity. Due to the great natural ability of lakes to accumulate energy and matter, their limnological properties are gradually transformed with time (Lange 1986). The differences in the pace and character of lake evolution result from the variation in the morphometry of lake basins and a varied impact of

their catchment areas (Bajkiewicz-Grabowska 2002). A heightened human-induced pressure leads to the transformation of water bodies, mainly in the processes of eutrophication, acidification and humication.

Lake Ostrowite is one of the best preserved lakes in the Bory Tucholskie National Park. It is situated in the district of Chojnice, 9 km to the north of the town Chojnice and 7 km to the north-east of the place Charzykowy. It is the first water body of the system called Struga Siedmiu Jezior (Seven Lakes Stream). What is more, it is the biggest (280.7 ha) and deepest (max. depth 43 m, mean 10.7 m) lake in the Bory Tucholskie National Park (Zdanowski 2004). It lies 124.2 m above sea level; it is 3900 m long and 1050 m wide; its basin capacity is 29,989,800 m³ (Choiński 1991). A long peninsula in the southern part divides the lake into a bigger western basin and smaller eastern one.

The lake belongs to seasonal flow-through water bodies (with an outflow to the north) and does not have surface tributaries (Nowicka 2006). The catchment slopes are fairly steep. In terms of the lithology of surface deposits, the catchment is of a clayey-sandy character (Bajkiewicz-Grabowska 2004). Podzolic soils developed here on the dominant outwash sands (Dąbrowska and Goszczyński 2000). The drainage basin has a surface area of 927.4 ha, 94.6% of which being covered by forests, mainly fresh coniferous ones, and the rest by meadows (Bajkiewicz-Grabowska 2004). Thanks to such conditions the lake has been subjected only to insignificant human-induced pressure.

The shore and bottom slopes of the lake basin are steep. The bottom sediments are composed of lacustrine chalk, calcareous gyttja and sands (Nowicka et al. 2002). Under such conditions the phytolittoral zone is dominated by stoneworts, which constitute the most numerous group of macrophytes (87.2% of biomass) and cover 25% of its total area (Chmara 2006). Nine species of the genus *Chara*, 3 of *Nitella* and 1 of *Nitellopsis* were recorded among the stoneworts (Chmara 2006). Small fragments of the bottom, especially in bays, are overgrown with pondweed patches, mainly *Potamogeton filiformis* Pers. *Myriophyllum spicatum* L., *Elodea canadensis* Rich. and *Batrachium circinatum* are also present. Submerged mosses, including the dominant *Fontinalis antipyretica* Hedw., can be found as well (Dąbrowska and Goszczyński 2000).

The lake is classified as bradyimictic with a 7-m-deep epilimnion. During the summer stagnation oxygen content decreases with depth. Only trace quantities of oxygen were recorded at 18 m. However, below 40 m anaerobic conditions prevail (Marszelewski and Jutrowska 2000). The water is transparent, characterised by high visibility and classified as of first-class purity. Consequently, the lake is considered to be one of most valuable hardwater lakes in Poland in terms of nature (Zdanowski and Stawecki 2004).

The aim of this work was to describe the environmental conditions of submerged plants in Lake Ostrowite and to determine their seasonal changes. The study consisted in the estimation of the physico-chemical water and sediment properties within the range of plant occurrence on the basis of monthly measurements over a period of three years.

Material and methods

The study was conducted in the years 2004-2006. Samples for the physico-chemical analyses of water and sediment were collected once a month from July 2004 to December 2006. Each time 3-5 water and sediment samples were taken from the central part of the submerged plant population's range (4-5m deep), as the greatest plant biomass is located there (Spence 1982; Kłosowski 1992; Chmara 2008). Moreover, the fieldwork at the site consisted in measuring visibility (using the Secchi disc), water temperature and oxygen content (with the OXI 96 oxygen meter with an EOT 196 electrode) and relative light intensity (with the LI-250 Light Meter) in the depth profile.

All the water and sediment samples were transported to a laboratory, where they were kept in a refrigerator at 4°C. The physico-chemical water and sediment analyses were performed according to methods recommended by Hermanowicz et al. (1999) and Eaton et al. (2005). In the water samples, pH (320/SET-1 pH meter with a SENTIX 97T electrode), electrolytic conductivity (LF 95 conductivity meter with a TETRA-CON 96 electrode) and redox potential (320/SET-1 pH meter with a METTLER P14805-S7/120 glass electrode) were measured. In addition, water colour was estimated by a comparative method on the platinum-cobalt scale. The following concentrations were determined: of calcium (by a complexometric versenate method in the presence of calcein as an indicator), of free carbon dioxide (by titration with a standard NaOH solution using phenolphthalein as an indicator), of hydrogen carbonate (by water titration with a standard HCl solution using methyl orange as an indicator), of carbonate (by titration with a standard HCl solution with phenolphthalein) and of humic acids (with a UV/Vis Aquamate spectrometer with a wavelength of 330 nm).

In the sediment, just as in the water, pH, electrolytic conductivity, redox potential and calcium content (after extraction from dry sediment with hydrochloric acid) were measured. Moreover, hydration (after drying of fresh sediment in a dryer at 105°C) and organic matter content (residue after ignition of dry sediment in a muffle furnace at 550°C) were determined.

Results

ENVIRONMENTAL CONDITIONS OF SUBMERGED PLANTS

Water in the central part of the phytolittoral zone is characterised by a slightly alkaline pH (7.30-8.24; Me=7.60). Its electrolytic conductivity is high ($186 \pm 26 \mu\text{S cm}^{-1}$; Me=181), which is indicative of a high concentration of dissolved mineral salts, especially calcium ions ($34.7 \pm 7.5 \text{ mg l}^{-1} \text{ Ca}$; Me=32.9). Redox potential is very variable, but oxidation processes dominate ($E_h 12 \pm 170 \text{ mV}$; Me=106). Free CO_2 concentration is low ($11 \pm 3 \text{ mg l}^{-1} \text{ CO}_2$; Me=10). The water lacks carbonate, but hydrogen carbonate concentration is high and not very changeable ($156 \pm 14 \text{ mg l}^{-1} \text{ HCO}_3^-$; Me=158). Water colouration is very weak ($9 \pm 3 \text{ mg l}^{-1} \text{ Pt}$; Me=9), which indicates a low content of dissolved organic matter, especially humic acids, whose concentration reaches $4.1 \pm 0.8 \text{ mg l}^{-1} \text{ HA}$ (Me=4.2).

Sediment pH is generally close to neutral, but it ranges from slightly acid to slightly alkaline (pH 6.56-7.86; Me=7.30). Calcium content is considerable ($32.7 \pm 7.2 \text{ mg Ca g}^{-1} \text{ d.w.}$; Me=30.5). Electrolytic conductivity is almost twice as high as in water and characterised by greater variability ($334 \pm 195 \mu\text{S cm}^{-1}$; Me=335). In

the sediment, reduction processes prevail, and redox potential is negative ($-179 \pm 76 \text{ mV}$; Me= -190) despite the mineral character of the sediment. Organic matter content ($1 \pm 1\%$; Me=1) and sediment hydration ($28 \pm 8\%$; Me=25) are very low.

The study showed that water is very well oxygenated in the plant occurrence zone (to a depth of 10 m). In the thermocline (6-7 m deep) it remained at a level of $12.2 \text{ mg l}^{-1} \text{ O}_2$ (Fig. 1). During summer stagnation a decrease in temperature was observed: from 24.2°C close to the surface to 8.8°C at a depth of 10 m. Visibility in water was very good (8 m). Light intensity gradually fell with depth, which indicates the optical uniformity of this environment (Fig. 1). The relative amount of PAR that reached a depth of 10 m constituted 1.3% of the value falling on the water surface. What is more, temperature and oxygen distribution analysed in spring 2006 showed (Fig. 1) that oxygen concentration was slightly higher than in summer. However, water oxygenation was about 90% and temperature was much lower. From a depth of 2 m water temperature and oxygenation were balanced in the entire profile. Light intensity gradually decreased with depth. At 8 m there was only 0.2% of light falling on the water surface (Fig. 1).

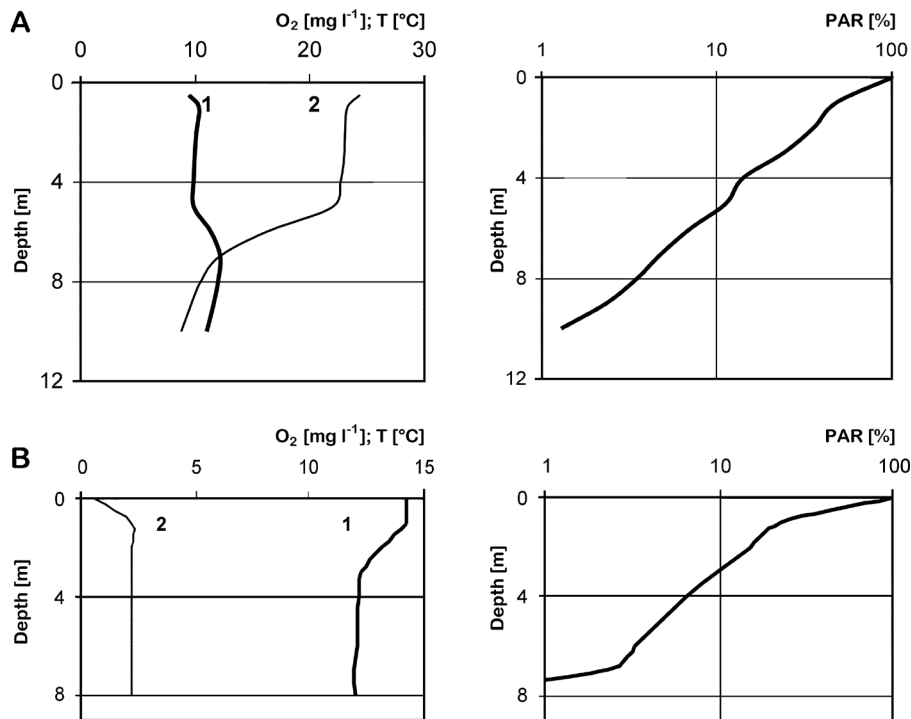


Fig. 1. Distribution of oxygen (1), temperature (2) and relative light intensity (PAR) in the depth profile in summer (A) and spring (B)

CHANGES OF WATER AND SEDIMENT PROPERTIES
DURING THE STUDY PERIOD

Water pH in Lake Ostrowite had always been slightly alkaline and during the study period it was subject to only slight fluctuations (Fig. 2). The highest pH values were recorded in summer (up to 8.21 in 2004) (Table 1), which is connected with the intensive photosynthesis of well developed and dense plant communities. In the other seasons pH was a little lower. The lowest pH values were observed in autumn and winter, when most plants had become dormant. The concentration of dissolved ions in the water was considerable and remained at a relatively constant level in the whole study period ($145\text{--}245\ \mu\text{S cm}^{-1}$; $\text{Me}=181$). The concentration of calcium dissolved in the water was also subject to only slight fluctuations ($27.3\text{--}45.0\ \text{mg l}^{-1}\ \text{Ca}$), and it was high all the time, which is typical of hardwater lakes. Redox potential exhibited wide fluctuations (Fig. 2). In summer it reached both positive (2004; $111\ \text{mV}$) and strongly negative (2005/2006; -169 and $-287\ \text{mV}$) values. In spring and autumn, when strong water mixing takes place, this feature was also very variable. Only in winter the potential was stable and always had positive values ($106\text{--}145\ \text{mV}$), which indicates the dominance of oxidation processes at low temperatures. Free CO_2 concentration was low and characterised by a small variation in the study

period. The lowest values ($7\ \text{mg l}^{-1}$) were recorded in autumn 2004 and 2005, whereas the highest in summer (2005; $16\ \text{mg l}^{-1}$). Contrary to carbon dioxide, the concentration of hydrogen carbonate was always high and ranged from 124 to $184\ \text{mg l}^{-1}$. Water colouration in the individual seasons was similar and always very low ($4\text{--}15\ \text{mg l}^{-1}\ \text{Pt}$; $\text{Me} = 9$). Humic acids concentration was also low ($2.7\text{--}5.7\ \text{mg l}^{-1}$; $\text{Me}=4.2$).

Sediment pH was lower than water pH (Table 2). The smallest values, indicating even a slightly acid environment, were observed in spring 2006 (pH 6.56). In the remaining seasons of the study period pH ranged from 7.24 to 7.86 and, just as in the water, the highest values were recorded in summer. Electrolytic conductivity was very changeable (from 128 to $530\ \mu\text{S cm}^{-1}$; $\text{Me}=335$). Redox potential was always negative, and its lowest values were noted in spring ($-224\ \text{mV}$) and summer ($-284\ \text{mV}$). Thus reduction processes prevailed all year long in the sediment. Calcium content, the same as in the water, was high, but also here it was characterised by only a minor variation during the whole study period (from 24.4 to $41.8\ \text{mg Ca g}^{-1}\ \text{d.w.}$; $\text{Me}=30.5$). The percentage of organic matter in the sediment was generally very small (approx 1.5%). As a result, the sediments are not well hydrated ($21.2\text{--}40.5\%$; $\text{Me}=24.6$) regardless of the time of year.

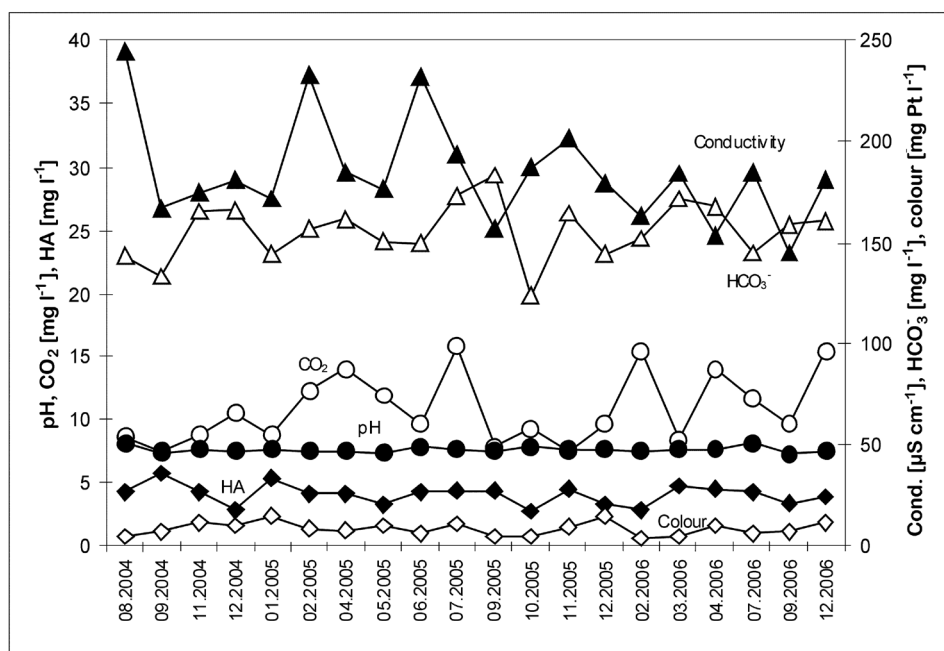


Fig. 2. Variations of pH, colour, conductivity and concentrations of carbon dioxide, hydrogen carbonate and humic acids in water in 2004-2006.

Table 1. Water properties

UNIT	Index	pH	Cond. [$\mu\text{S cm}^{-1}$]	Eh [mV]	Ca ²⁺ [mg l ⁻¹]	CO ₂ [mg l ⁻¹]	HCO ₃ ⁻ [mg l ⁻¹]	HA [mg l ⁻¹]	Colour [mg l ⁻¹ Pt]
Summer 2004	26.08	8.21	245	111	40.1	9	143	4.2	5
Autumn 2004	18.09	7.39	167	nm	nm	7	133	5.7	7
	20.11	7.63	174	nm	nm	9	165	4.3	12
Winter 2004	18.12	7.50	181	nm	nm	11	166	2.8	10
	15.01	7.63	171	nm	nm	9	144	5.4	15
	12.02	7.49	233	106	nm	12	158	4.1	9
Spring 2005	17.04	7.50	185	-178	32.9	14	162	4.1	8
	22.05	7.45	176	nm	nm	12	151	3.3	10
	16.06	7.84	232	110	45.0	10	149	4.3	6
Summer 2005	17.07	7.70	194	-162	27.9	16	173	4.4	11
Autumn 2005	23.09	7.57	157	nm	nm	8	184	4.4	5
	20.10	7.94	188	nm	nm	9	124	2.7	5
	19.11	7.61	202	179	41.9	7	164	4.5	9
Winter 2005	20.12	7.60	180	nm	nm	10	144	3.2	15
	24.02	7.52	163	145	nm	15	152	2.9	4
Spring 2006	24.03	7.66	185	83	27.3	8	171	4.7	5
	20.04	7.67	154	nm	nm	14	168	4.5	10
Summer 2006	23.07	8.18	185	-287	28.0	12	145	4.2	7
Autumn 2006	14.09	7.30	145	nm	nm	10	159	3.4	7
Winter 2006	21.12	7.51	181	nm	nm	15	160	3.9	12

nm – not measured

Table 2. Sediment properties

Unit	Index	pH	Coductivity [$\mu\text{S cm}^{-1}$]	Eh [mV]	Ca [mg g ⁻¹ d.w.]	Organic matter [%]	Hydration [%]
Summer 2004	26.08.	7.72	180	-203	30.9	1.9	26.1
Spring 2005	16.06.	7.24	511	-224	24.4	0.8	40.5
Summer 2005	17.07.	7.86	164	-177	27.9	2.7	33.8
Autumn 2005	19.11.	7.20	491	-98	41.8	1.9	22.9
Spring 2006	24.03.	6.56	128	-85	41.4	0.6	21.2
Summer 2006	23.07.	7.36	530	-284	30.1	1.0	23.0

SEASONAL VARIABILITY OF PHYSICAL AND CHEMICAL WATER AND SEDIMENT PROPERTIES

The analysis of variance conducted for individual seasons showed a significant variability of water and sediment properties. At a significance level of $p < 0.05$, electrolytic conductivity, concentrations of HCO₃⁻ and humic acids as well as colour were constant in the water, whereas in the sediment all the studied properties except pH. The remaining features exhibited statistically significant differences. The con-

ducted RIR Tukey's test confirmed the invariability of the above-mentioned properties of the aquatic environment and allowed indicating the seasons in which conditions in the lake differ most.

In spring water pH was slightly alkaline and almost invariable (pH 7.64 ± 0.15 ; Me=7.67). Conductivity also displayed low variability ($186 \pm 23 \mu\text{S cm}^{-1}$; Me=184), while calcium concentration was of medium variability and high all the time ($35.1 \pm 9 \text{ mg l}^{-1}$; Me=32.9). Redox potential exhibited marked fluctuations (-178 do 110 mV), but it was generally positive

(Me=83). By and large, the other water properties were constant. The concentration of free CO₂ (12 ± 3 mg l⁻¹; Me=12) was low, while that of hydrogen carbonate high (160 ± 10 mg l⁻¹; Me=162). The content of humic acids was low (4.2 ± 0.5 mg l⁻¹; Me=4.3), due to which water was almost colourless (7 ± 2 mg l⁻¹; Me=6).

The sediments collected in spring were characterised by a lower pH than water (6.47-7.47; Fig. 3). On the other hand, their electrolytic conductivity was similar, but more variable (281 ± 211 μS cm⁻¹; Me=146). Calcium concentration was considerable and also changeable (32.9 ± 12 mg Ca g⁻¹d.w.; Me=32.9). Redox potential was always negative and did not show such variability as in water (-140 ± 86 mV; Me= - 147). The percentage of organic matter was very small (1.0 ± 0.1%). The sediments were mineral and poorly hydrated (36 ± 10.6%; Me=23.6).

In summer water pH ranged from 7.65 to 8.28 (Me=8.16) and was higher than in spring (p<0.001; Fig. 3). Conductivity (199 ± 23 μS cm⁻¹; Me=188), concentrations of calcium (32.0 ± 7.8 mg l⁻¹; Me=28.0), carbon dioxide (12 ± 4 mg l⁻¹; Me=12), hydrogen carbonate (154 ± 1 mg l⁻¹; Me=145) and humic acids (4,3 ± 0,1 mg l⁻¹; Me=4,2), water colour (8 ± 3 mg l⁻¹; Me=7) as well as redox potential (-147 ± 158 mV; Me= -165) were almost the same as in the previous season and did not exhibit statistically significant differences.

The sediment collected in summer had a slightly alkaline pH (6.92-7.91; Me=7.81) and differed from the spring samples (p<0.001). Sediment conductivity was considerable and in addition fluctuated widely between 82 and 772 μS cm⁻¹ (Me=218; p=0.003). In spring, the values of such features as redox potential (-224 ± 109 mV; Me= - 262), contents of calcium (29.6 ± 1.5 mg Ca g⁻¹ d.w.; Me=30.1) and organic matter (2 ± 1.4%) as well as sediment hydration (27.9 ± 8.3%; Me=25.3) did not differ from those recorded in summer.

In autumn environmental conditions in the lake were not different from those observed in summer and spring. This refers mainly to water conductivity, contents of hydrogen carbonate and humic acids in the water and water colour. In the sediment, values of all properties did not differ in a statistically significant way (Fig. 3). Water pH (7.30-7.57) in autumn was lower than in summer (p<0.001) and very similar to the spring pH. Redox potential was high, constant (179 ± 1 mV) and comparable with the spring values, and differed from the summer ones at a level of p=0.004. Calcium concentration (41.9 ± 0.8 mg l⁻¹ Ca) was much higher than in summer (p=0.020) and spring (p=0.040). The quantity

of free CO₂ (8 ± 1 mg l⁻¹; Me=8) was smaller than in the previous season (p=0.044).

In winter water pH was slightly acidic (pH 7.50-7.60), the same as in autumn and spring, but decidedly lower than in summer (p=0.001; Fig. 3). The remaining water properties did not differ in comparison with the other seasons.

Discussion

The seasonal changes of physico-chemical conditions in water bodies depend on many factors, including climatic, geomorphological and biological conditions. In natural water bodies or those transformed only to a small extent the variability of environmental conditions over the year is generally low. This is guaranteed by well-preserved vegetation in the catchment area and a stable hydrological system (Bajkiewicz-Grabowska 2002). However, if the catchment is influenced by human activity and regulation of water conditions, the seasonal variability of many properties of lake water increases (Minshall et al. 1985). Mountain lakes, practically free of the impact of human pressure as they are, are considered to be model lakes and good objects of study on the seasonal variability of the aquatic environment. The seasonal changes observed in them are connected with altitude (and consequently temperature and length of ice-cover period), trophic level, morphometry (size and depth), catchment type and pollution of precipitation (Tait and Thaler 2000; De Bernardi et al. 1996; Rogora et al. 2001). Nevertheless, they are very susceptible to changes: even small differences in temperature (1-2°C) result in significant changes in water chemistry as well as flora and fauna (Koinig et al. 1998; Skjelkvale and Wright 1998).

The studied water body is a hardwater and oligo-/mesotrophic lake with favourable morphometric properties (large area and considerable depth) which guarantee low vulnerability to transformations. Moreover, the area where Lake Ostrowite is situated is characterised by a high degree of geological uniformity. Sandy and barren soils of the catchment are covered with pine forests (Tobolski and Kochanowski 2002), and the human impact is minimised by the situation of the lake within the Bory Tucholskie National Park. All these features of the lake and its surroundings influenced the low seasonal variability of physico-chemical properties of the aquatic environment observed in this study.

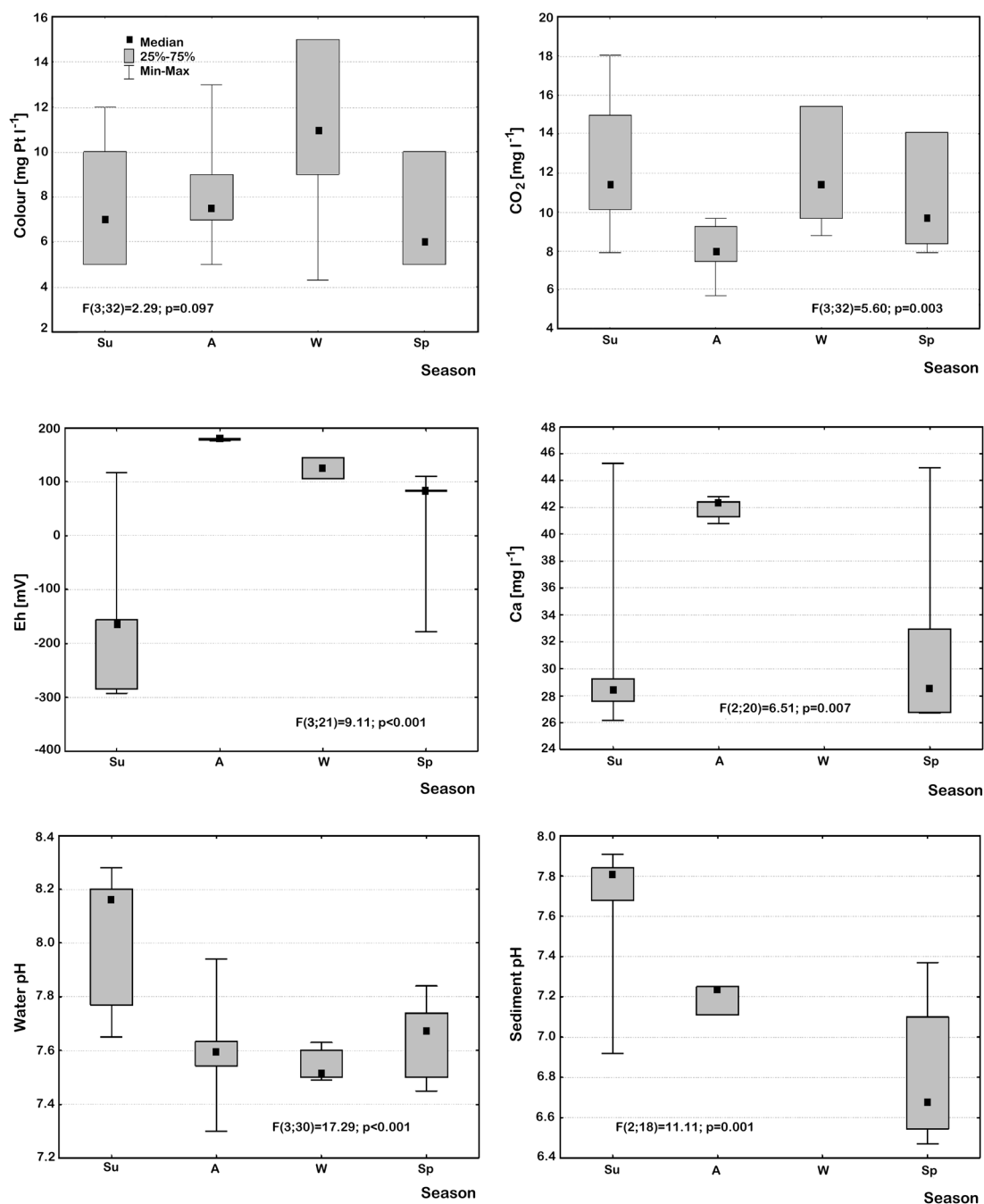


Fig. 3. Water and sediment properties in summer (Su), autumn (A), winter (W) and spring (Sp)

In this study it was found that only a few water and sediment properties exhibit seasonal variability (see Fig. 3). This results from the visible dominance of autochthonous matter in the ecosystem (there is little flow through the lake) and high stability of the submerged vegetation structure (a high percentage of evergreen plants) which, in turn, stabilises the physico-chemical conditions (Szmeja 1992; van Breemen 1995;

Limpens et al. 2003a, b; Malmer et al. 2003). Lakes intensively fed with allochthonous matter (Perdue and Gjessing 1990), as well as water bodies whose plants are not active in winter (they undergo diapause), are much more variable.

The value of pH is subject to frequent fluctuations in almost all types of water bodies, which makes it one of the most variable features of the aquatic en-

vironment. It mainly depends on the concentration of carbon dioxide (Tait and Thaler 2000), which is bound in photosynthesis and released in the processes of the aerobic decomposition of organic matter and respiration. That is why the lowest pH and the highest concentration of CO_2 are recorded in winter (Mosello et al. 2002), especially close to the ice cover (Camarero et al. 1995; Camarero et al. 1999). Identical changes in pH were obtained during this study (the highest values in summer; see Fig. 3), but they were not consistent with the variations in CO_2 concentrations (Fig. 3). In summer the high pH results from intense photosynthetic activity, whereas in the other seasons pH is very level and slightly lower than in summer, as photosynthesis is not as intense due to lower temperatures. The stability of pH stems from a similar amount of carbon dioxide dissolved in water over the year (only in autumn it is slightly lower). This is typical of calcium-rich hardwater lakes. In winter, but also in spring and autumn, as organic matter decomposes, the resulting carbon dioxide shifts the balance towards insoluble CaCO_3 , which accumulates on plants for example (Wetzel 1983). In summer, when plants use CO_2 in photosynthesis, it is replenished not only from the atmosphere, but also from calcite decomposition caused by phosphoric acid dissolved in water (Stumm and Morgan 1996). What is more, hardwater lakes are dominated by plants that use HCO_3^- in photosynthesis, such as *Myriophyllum spicatum* L. or *Elodea canadensis* Rich., and additionally protect the lakes against pH changes. Nevertheless, during periods of very strong photosynthesis, even in such well-buffered water bodies, especially those with a higher trophic level, pH may rise substantially in summer, as the recreation of balance is delayed.

Such features of the aquatic environment as the content of dissolved organic and mineral compounds are dependent on water and sediment pH. Most physical and chemical reactions that take place in aquatic ecosystems are influenced by pH (Lampert and Sommer 1996). It should also be mentioned that submerged vegetation developing in a water body contributes to the changes in chemical and physical water properties, especially underwater *Chara* spp. carpets, which assist in maintaining high water clarity (Blindow et al. 2002). Dense communities of submerged plants accumulate great quantities of

nutrients and remove them from the nutrient cycle (Blindow 1992; Kufel and Ozimek 1994). They also provide shelter for zooplankton (Lauridsen and Buenk 1996), which plays an important role in maintaining water clarity by limiting the development of phytoplankton (Timms and Moss 1984). Jeppesen et al. (1994) found that if 30% of the lake bottom is covered with vegetation, it suffices to maintain constant environmental conditions and water clarity. The water body under study fulfils this criterion. The submerged vegetation in it is dominated by stoneworts covering 25% of the phytolittoral (Chmara 2006; Skurzyński 2007), which contributes significantly to the stability of environmental conditions. Perennial submerged vegetation also aids in preventing sediment resuspension (Scheffer et al. 1993; Hanson and Butler 1994) by reducing wind impact (Hamilton and Mitchell 1996). The abundant occurrence of *Chara* assists in inhibiting phytoplankton development (Jones et al. 1996). According to Blindow and Hootsmans (1991), this may result from the fact that stoneworts produce allelopathic substances or from the limited accessibility of phosphorus (Forsberg et al. 1990), which strongly precipitates as apatite.

The low seasonal variability of pH and the other water properties in the studied lake indicates the stability of its environmental conditions. This can undoubtedly be attributed to submerged plants, especially stoneworts, which guarantee the proper functioning of the lake and maintain high water clarity. Owing to the fact that this water body has been subject to hardly any human-induced pressures, it can be regarded as a model object of study on the extent and causes of transformations of lakes and submerged vegetation habitats. That is why a constant control of its environmental conditions is highly recommended.

Acknowledgments

The authors are deeply grateful to Professor Józef Szmeja for helpful comments received while this article was being written. We would also like to thank Marek Merdalski, MSc, for his help in field work. This work was financed from the funding sources for education in 2007-2010 as experimental project no. N N304 4113 33 and 2004-2007-project no. 2 P04G 00127.

References

- Bajkiewicz-Grabowska E., 2002, Obieg materii w systemach rzeczno-jeziornych (Circulation of matter in river-lake systems), Wyd. UW, Warszawa, p. 274 (in Polish).
- Bajkiewicz-Grabowska E., 2004, Podatność jezior na eutrofizację (Vulnerability of lakes to eutrofication), [in:] Zdanowski B., Hutorowicz A., Białokoz W. (eds), Ekosystemy wodne Parku Narodowego „Bory Tucholskie” (Aquatic ecosystems of the Bory Tucholskie National Park); Wyd. IRŚ, Olsztyn: 17-32 (in Polish).
- Blindow I., 1992, Decline of charophyte during eutrophication: comparison with angiosperms, *Freshwater Biol.* 28: 9-14.
- Blindow I., Hargeby A., Andersson G., 2002, Seasonal changes of mechanisms maintaining clear water in a shallow lake with abundant *Chara* vegetation, *Aquat. Bot.* 72: 315-334.
- Blindow I., Hootsmans M.J.M., 1991, Allelopathic effects from *Chara* spp. on two species of unicellular green algae, [in:] Hootsmans M.J.M., Vermaat J.E., (eds), Macrophytes as a key to understanding changes caused by eutrophication in shallow freshwater ecosystems, Institute for Hydraulic and Environmental Engineering, Delft, The Netherlands: 139-144.
- Camarero L., Catalan J., Boggero A., Marchetto A., Mosello R., Psenner R., 1995, Acidification in high Mountain lakes in central, southwest and southeast Europe (Alps, Pyrenees, Pirin), *Limnologia*, 25(2): 141-156.
- Camarero L., Felip M., Ventura M., Bartumeus F., Catalan J., 1999, The relative importance of the planktonic food web in the carbon cycle of an oligotrophic mountain lake in a poorly vegetated catchment (Redó, Pyrenees), *J. Limnol.* 58: 203-212.
- Chmara R., 2006, Roślinność podwodna jeziora Ostrowite (Submerged vegetation of Lake Ostrowite), [in:] Kowalewski G., Milecka K. (eds), Jeziora i torfowiska Parku Narodowego Bory Tucholskie (Lakes and peatlands of the Bory Tucholskie National Park), PN Bory Tucholskie, Charzykowy: 73-76.
- Chmara R., 2008, Przyczyny zróżnicowania struktury roślinności podwodnej w jeziorach na obszarach sandrowych Borów Tucholskich (Causes of diversity of submerged vegetation structure in the lakes located on the outwash plains of Bory Tucholskie), Uniwersytet Gdański, Wdz. Biologii, Gdańsk, p. 146 (dissertation) (in Polish).
- Choiński A., 1991, Katalog jezior polskich. Część pierwsza – Pojezierze pomorskie (Catalogue of Polish lakes. Part I: Pomeranian Lakeland), Wyd. UAM, Poznań, p. 221.
- Dąbrowska B., Goszczyński J., 2000, Hydrofity Strugi Siedmiu Jezior na terenie Parku Narodowego Bory Tucholskie (Hydrophytes of the Seven Lakes Stream in the Bory Tucholskie National Park), [in:] Banaszak J., Tobolski K. (eds), Park Narodowy Bory Tucholskie; stan poznania na tle kompleksu leśnego Bory Tucholskie (Level of knowledge of the Bory Tucholskie National Park compared with the forest complex of Bory Tucholskie), Wyd. Uczelniane Akademii Bydgoskiej, Bydgoszcz: 245-260 (in Polish).
- De Bernardi R., Calderoni A., Mosello R., 1996, Environmental problems in Italian lakes Maggiore and Orta as successful examples of correct management leading to restoration, *Verh. Internat. Verein. Limnol.* 26: 123-138.
- Eaton A.D., Clesceri L.S., Rice E.W., Greenberg A.E., 2005, Standard methods for the examination of water and wastewater, 21th Edition, American Public Health Association, American Water Works Association and Water Environment Federation, Washington, p. 1368.
- Forsberg C., Kleiven S., Willén T., 1990, Absence of allelopathic effects of *Chara* on phytoplankton in situ, *Aquat. Bot.* 38: 289-294.
- Hamilton D.P., Mitchell S.F., 1996, An empirical model for sediment resuspension in shallow lakes, *Hydrobiologia* 317: 209-220.
- Hanson M.A., Butler M.G., 1994, Responses to food web manipulation in a shallowwaterfowl lake, *Hydrobiologia* 279/280: 457-466.
- Hermanowicz W., Dożańska W., Dojlido J., Kozirowski B., 1999, Fizyczno-chemiczne badanie wód i ścieków (Physico-chemical studies of the water and sewage), Arkady, Warszawa, p. 556 (in Polish).
- Jeppesen E., Søndergaard M., Kanstrup E., Petersen B., Eriksen R.B., Hammershøj M., Mortensen E., Jensen J.P., Have A., 1994, Does the impact of nutrients on the biological structure and function of brackish and freshwater lakes differ?, *Hydrobiologia* 275/276: 15-30.
- Jones J.I., Hardwick K., Eaton J.W., 1996, Diurnal carbon restrictions on the photosynthesis of dense stands of *Elodea nuttallii* (Planch.) St. John, *Hydrobiologia* 340: 11-16.
- Kłosowski S., 1992, Temporal and spatial variation of habitat conditions in the zonation of littoral plant communities, *Aquat. Bot.* 43: 199-208.
- Koinig K. A., Schmidt R., Sommaruga-Wögrath S., Tessadri R., Psenner R., 1998, Climate Change as the primary cause for pH shifts in a high alpine lake, *Water Air Soil Pollut.* 104: 167-180.
- Kufel L., Ozimek T., 1994, Can *Chara* control phosphorus cycling in Lake Luknajno (Poland)?, *Hydrobiologia* 275/276: 277-283.
- Lampert W., Sommer U., 1996, Ekologia wód śródlądowych (Ecology of inland waters), Wyd. Nauk. PWN, Warszawa, p. 389 (in Polish).
- Lange P., 1986, Fizyczno-limnologiczne uwarunkowania tolerancji systemów jeziornych Pomorza (Physical and limnological conditions of tolerance of Pomeranian lake systems), *Zesz. Nauk. UG, Rozprawy i Monografie* 79, Gdańsk, p. 177 (in Polish).
- Lauridsen T., Buenk I., 1996, Diel changes in the horizontal distribution of zooplankton in the littoral zone of two shallow eutrophic lakes, *Arch. Hydrobiol.* 137: 161-176.
- Limpens J., Berendse F., Klees H., 2003a, N deposition affects N availability in interstitial water, growth of *Sphagnum* and invasion of vascular plants in bog vegetation, *New Phytol.* 157: 339-347.

- Limpens J., Tomassen H.B.M., Berendse F., 2003b, Expansion of *Sphagnum fallax* in bogs, striking the balance between N and P availability, *J. Bryol.* 25: 83-90.
- Malmer N., Albinsson C., Svensson B.M., 2003, Interferences between *Sphagnum* and vascular plants: effects on plant community structure and peat formation, *Oikos* 100: 469-482.
- Marszelewski W., Jutrowska E., 2000, Wstępna inwentaryzacja hydrologiczna Parku Narodowego Bory Tucholskie (Initial hydrological inventory of the Bory Tucholskie National Park), [in:] Banaszak J., Tobolski K. (eds), Park Narodowy Bory Tucholskie; stan poznania na tle kompleksu leśnego Bory Tucholskie (Level of knowledge of the Bory Tucholskie National Park compared with the forest complex of Bory Tucholskie), Bydgoszcz: 49-68 (in Polish).
- Minshall G.W., Cummius K.W., Petersen R.C., Cushing C.E., Bruns D.A., Sedell J.R., Vannote R.L., 1985, Developments in stream ecosystem theory, *Can. J. Fish. Aquat. Sci.* 42: 1045-1055.
- Mosello R., Lami A., Marchetto A., Rogora M., Wathne B., Lien L., Catalan J., Camarero L., Ventura M., Psenner R., Koinig K., Thies H., Sommaruga-Wögrath S., Nickus U., Tait D., Thaler B., Barbieri A., Harriman R., 2002, Trends in the water chemistry of high altitude lakes in Europe, *Water Air Soil Poll.: Focus* 2: 75-89.
- Nowicka B., 2006, Hydrogeologia i hydrologia jeziora Ostrowite (Hydrogeology and hydrology of Lake Ostrowite), [in:] Kowalewski G., Milecka K. (eds), Jeziora i torfowiska Parku Narodowego Bory Tucholskie (Lakes and peatlands of the Bory Tucholskie National Park), PN Bory Tucholskie, Charzykowy: 63-72.
- Nowicka B., Wicik B., Żmudzcka E., Lenartowicz M., Woronko D., Skrzypczuk J., Bajkiewicz-Grabowska E., Wiśniewski R., 2002, Operat biogeochemii krajobrazu i zasobów wodnych (Report on the biogeochemistry of landscape and water resources), NFOŚ, Warszawa (in Polish).
- Perdue E.M., Gjessing E.T., 1990, Organic acids in aquatic ecosystems. Dahlem Konferenzen, Chichester: John Wiley & Sons Ltd., p. 345.
- Rogora M., Mosello R., Marchetto A., Boggero A., Tartari G., 2001, Long-term variations in the hydrochemistry of Alpine lakes in the Ossola and Sesia Valleys (Central Alps) in relation to atmospheric input and climate change, *Studi Trent. Sci. Nat., Acta Biol.* 78: 59-69.
- Scheffer M., Hopper S.H., Meijer M.-L., Moss B., Jeppesen E., 1993, Alternative equilibria in shallow lakes, *Trends Ecol. Evol.* 8: 275-279.
- Skjelkvale B.L., Wright R.F., 1998, Mountain lakes; sensitivity to acid deposition and global climate, *Ambio* 27: 280-286.
- Skurzyński P., 2007, Wpływ warunków środowiska na pomnażanie wegetatywne i kiełkowanie oospor *Chara rudis* A. Braun. (Effect of environmental conditions on the vegetative reproduction and germination of *Chara rudis* A. Braun. Oospores), Uniwersytet Gdański, Wydz. BGiO, Gdańsk, p. 51 (dissertation) (in Polish).
- Spence D.H.N., 1982, The zonation of plants in freshwater lakes, *Adv. Ecol. Res.* 12: 37-125.
- Stumm W., Morgan J.J., 1996, Aquatic chemistry, chemical equilibria and rates in natural waters, Wiley Interscience Publication, New York, p. 1022.
- Szmeja J., 1992, Struktura, organizacja przestrzenna i demografia populacji isoetydów (Structure, spatial organization and demography of isoetid populations), *Zesz. Nauk. UG, Rozprawy i Monografie* 175, Gdańsk, p. 137 (in Polish).
- Tait D., Thaler B., 2000, Atmospheric deposition and lake chemistry trends at a high mountain site in the eastern Alps, *J. Limnol.* 59(1): 61-71.
- Timms R.M., Moss B., 1984, Prevention of growth of potentially dense phytoplankton populations by zooplankton grazing, in the presence of zooplanktivorous fish, in a shallow wetland ecosystem, *Limnol. Oceanogr.* 29: 472-486.
- Tobolski K., Kochanowski J., 2002, Pięć lat Parku Narodowego „Bory Tucholskie” (Five years of the Bory Tucholskie National Park), [in:] Banaszak J., Tobolski K. (eds), Park Narodowy „Bory Tucholskie” na tle projektowanego rezerwatu biosfery (Bory Tucholskie National Park against the planned biosphere reserve), Charzykowy: 9-22 (in Polish).
- Van Breemen N., 1995, How *Sphagnum* bogs down other plants. *Trends Ecol. Evol.* 10: 270-275.
- Wetzel R.G., 1983, *Limnology*, W. B. Sanders College Publ., Philadelphia, p. 767.
- Zdanowski B., 2004, Ogólna charakterystyka ekosystemów wodnych Parku Narodowego „Bory Tucholskie” (General characteristics of aquatic ecosystems of the Bory Tucholskie National Park), [in:] Zdanowski B., Hutorowicz A., Białokoz W. (eds), Ekosystemy wodne Parku Narodowego „Bory Tucholskie” (Aquatic ecosystems of the Bory Tucholskie National Park); Wyd. IRŚ, Olsztyn: 7-14 (in Polish).
- Zdanowski B., Stawecki K., 2004, Zagrożenia antropologiczne jezior (Human-induced threats to lakes), [in:] Zdanowski B., Hutorowicz A., Białokoz W. (eds), Ekosystemy wodne Parku Narodowego „Bory Tucholskie” (Aquatic ecosystems of the Bory Tucholskie National Park); Wyd. IRŚ, Olsztyn: 59-72 (in Polish).