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OBSERVATIONS OF SELECTED CHEMICAL COMPONENTS OF MEROMICTIC LAKE ZAPADŁE WATERS IN 1990–1993, 2000–2001 AND 2005–2006

RENATA TANDYRAK*, MARIUSZ TEODOROWICZ, JOLANTA GROCHOWSKA

University of Warmia and Mazury in Olsztyn, Faculty of Environmental Protection and Fishery, Chair of Environmental Protection Engineering
Prawocheńskiego str. 1, 10-957 Olsztyn, Poland
*Corresponding author e-mail: renatat@uwm.edu.pl

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Abstract: Studied was a small (4.6 ha) meromictic lake situated in a deep land hollow surrounded by a high-inclination slope. The lake was made shallower two times (from 20 to 18 m) by collapsed shores. It is fed by underground waters and has relatively constant outflow. Limited water dynamics reduced the epilimnion thickness (from 4 to 2 m) and influenced the monimolimnion setting below 13 m depth with a characteristic small (0.2°C) temperature increase in the vertical profile and a permanent deoxygenation of the water below 7–11 m depth. The relationship between the organic matter parameters BOD_5 and COD-Mn before the shore collapse revealed the dominance of matter produced in the reservoir. In the final period the situation was opposite. In the monimolimnion allochthonous matter accumulated which due to anaerobic decomposition generated large amounts of ammonium. Observed in the same water layer was also a decrease of the conductivity.

INTRODUCTION

Meromictic lakes, characteristic for limited water dynamics, make a small but expanding group of water reservoirs. Usually, they are situated in land hollows and surrounded by obstacles hindering wind access to the water table. Typically they freeze late and long lasting summer stratification sets on quickly.

There are many reasons for meromixis [5], yet the main factor fostering this phenomenon is the lakes morphometry. Crucial is the role of small surface area related to depth, expressed by the high value of the relative depth index [4]. Water dynamics is further limited by increased primary production and the resultant accumulation of decomposition products in the near-bottom water layers, inflow of salty spring waters on the lake bottom or waste water disposal.

In Poland, meromixis has been recognized in a little more than ten reservoirs [18], including Lake Zapadłe [19, 20]. Localization of this lake is the reason for reduced exposure to wind activity [13] and therefore for the diminished intensity of water circulation in the lake.

The aim of this study was to examine the selected physicochemical parameters of water collected over 16 years of research and to confirm the meromictic character of Lake Zapadłe.

MATERIAL AND METHODS

Lake Zapadłe is located in the Mazurian Lakeland, the Ostróda region, approx. 2 km east of the Łukta village. The main morphometry characteristics [16] are shown in Table 1.

Table 1. Selected morphometry characteristics of Lake Zapadłe [16]

Parameter	Value
Water table ordinate (m above the sea level)	87.9
Water table surface [ha]	4.6
Maximal depth [m]	18
Mean depth [m]	10.7
Relative depth	0.084
Maximal length [m]	275
Maximal width [m]	225
Volume [thousand m^3]	494

The lake is a typical postglacial melt-out reservoir. Two periods should be pointed out in its history: the first when backward erosion by the outflowing stream lowered the water table by a few meters and the second, in spring 2000, when the activity of beavers lowered the water table by 2.2 m (with parallel water surface area reduction from 5 ha to 4.6 ha). Beavers keep on being active in that area with the evidence observed many times during the field studies.

Near Zapadłe, a Lake Isąg can be found which is currently set 7 m higher. Although located in another drainage basin, it affects Lake Zapadłe in a particular way – heavy water leaking from Isąg causes ongoing shoreline destruction in Lake Zapadłe. This high input of underground waters is the reason why even at the low or periodical surface inflow Zapadłe sustains a relatively constant outflow of 30 $dm^3 \cdot s^{-1}$ on the average.

The lake bowl sits in a deep land hollow. The northern, western and southern shores form steep and high slopes (approx. 20 m heigh) covered with an old tree stand. Total drainage basin of the lake is 185.9 ha with the dominance of arable land (62%) and forests (35%). Two other lakes – Zarośnięte and Polne – occupy 3% of the area. The drainage basin draining directly to the lake is rather small, i.e., 9.4 ha and in 70% afforested. The rest of the area is cultivated land.

In this paper are presented the results of the research done in 1990–1993 and 2001–2002 (bimonthly in average). The water samples were collected four times from June 2005 to November 2006 in the all seasons of lacustrine year. Water samples for the complete chemical analyses were taken from the surface layer (1 m) and at 5, 10, 12, 15 and 17 m depth, over the deepest site in the lake determined with the help of the bathymetric chart and GPS. Additionally, each time a temperature/oxygen profile was done based on the readings from every meter of the depth. Water samples were taken using 3.5-l Ruttner apparatus with a in-built mercury thermometer (0.2°C accuracy). Chemical analyses were conducted in accordance with the methods by Hermanowicz *et al.* [6].

RESULTS AND DISCUSSION

The distinctive feature of meromictic lakes is the lack of complete water turnover in spring and autumn that affects temperature settings in the lake (Fig. 1). In the vertical temperature profile observable is an increase towards the bottom [18]. The same tendency has been quite regularly observed in the discussed lake. At the end of the study period a small (0.2°C) characteristic temperature increase was observed between 12 and 13 m depth (June 2005) or slightly higher between 11 and 12 m depth (May 2006). On that ground, the water layer below 13 m depth was determined as the monimolimnion. Incomplete water mixis caused small temperature oscillations in the near-bottom water layers: in the range of 5.8–6.2°C at the beginning of the study and 5.2–6.3 after the water table dropped. Another outcome of the incomplete water circulation was the temperature decrease in the hypolimnion. The mean values of this parameter decreased from 6.1–6.6°C at the beginning of the research period to 5.2–5.8°C in 2005–2006. Over the years, also the epilimnion thickness has diminished. In 1990 and 1991 it was 3–4 m deep, whereas at the end of the study the thickness varied between 1 and 2 m. The main obstacle for the water exchange between the epi- and hypolimnion was the metalimnion, varying throughout the research with regard to thickness and location (4–8 m in the 1990s, 2–4 m currently). Primarily, the maximum temperature gradient was deeper, i.e., in August 1990 it was between 4 and 5 m depth and equaled 3.8°C, whereas since 2000 it has been always between 2 and 3 m. The highest temperature gradient was noted in July 2001 and it amounted to 6.4°C.

Limited water dynamics is a result of insufficient wind sheer stress on the water surface which is due to the lakes localization and enclosure by high slopes. Equally important is the relationship between the vertical and horizontal dimensions of the lake expressed as relative depth index. The relative depth, according to Halbfass, calculated for the max. depth of 20.2 m (before 2000) was 0.0993. After the shores had collapsed and the max. depth diminished the value of the index remained high (0.0839) and only a little lower than those quoted by Choiński [2] as the extreme values for the lakes of the Mazurian Lakeland.

Poor water circulation affected the oxygenation (Fig. 2). Spring turnover transferred the gas down to 8–10 m depth while the autumn circulation, even at full homothermy (28 Nov 06), to the depth of 7–11 m. The winter research (22 Jan 02, 23 Feb 06) revealed oxygen deficits, most likely caused by the decay of organic matter accumulated in the lake [15].

The quantity of organic matter can be estimated on the ground of the BOD_5 and COD-Mn measurements (Fig. 3) At the end of the research (2005–2006), the BOD_5 values below the depth of 15 m ranged from 7.5 to 8.1 mg $O_2 \cdot dm^{-3}$, while COD-Mn was higher: 7.4–12.2 mg $O_2 \cdot dm^{-3}$ at 15 m and 10.1–12.8 mg $O_2 \cdot dm^{-3}$ in the deepest layer (Tab. 2). The relationship between these parameters indicates the dominance of the matter imported to the lake over the autochthonous matter which seems rather obvious provided that the lake is a through-flow reservoir, the steep shores are strongly eroded, water permeates from the nearby Lake Isąg, and the way of the drainage basins use. An opposite situation had been observed before the shores collapsed in the spring 2000. The parameters of organic matter, both allo- and autochthonous, were higher and the relationship showed obvious dominance of the substance produced in the lake.

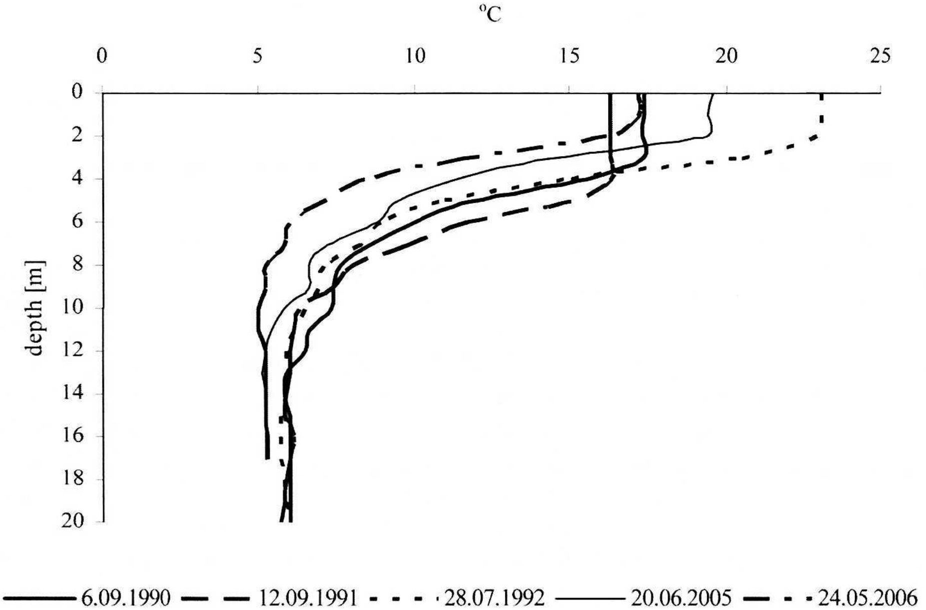

Fig. 1. Summer temperature profiles in the waters of Lake Zapadłe at the start and at the end of the research

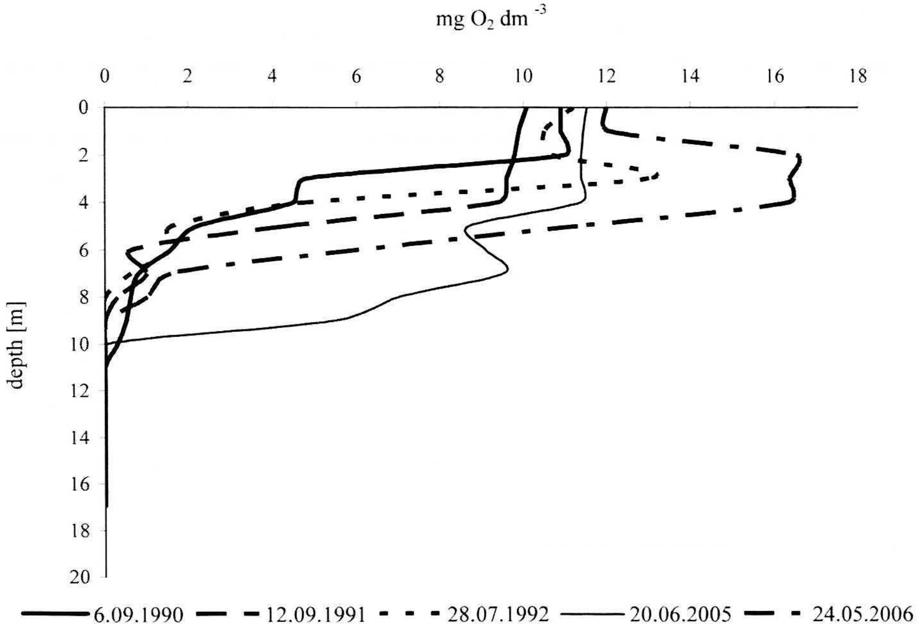

Fig. 2. Summer oxygen profiles in the waters of Lake Zapadłe at the start and at the end of the research

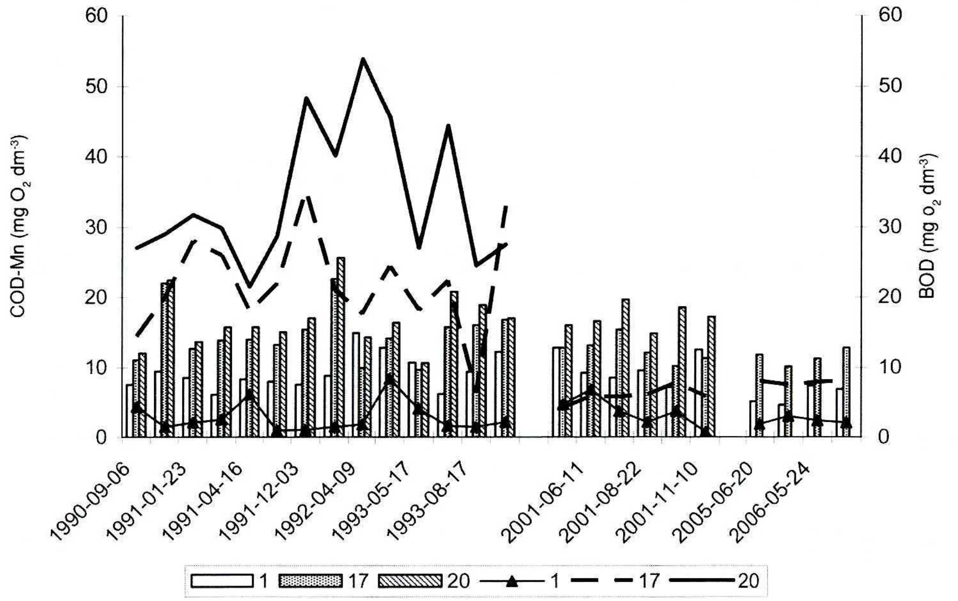

Fig. 3. Changes of organic matter content in the waters of Lake Zapadłe

Conductivity, the measurement commonly practiced in hydrochemical studies, provides information about water mineralization in relation to its feeding structure and participation of the underground alimentation [10, 11]. High values of this parameter (in the discussed lake from 440 to 484 $\mu S \cdot cm^{-1}$) are typical for lakes fed from underground sources (in the discussed case – water percolation from Lake Isąg) and for lakes serving long time as recipients of the heavily polluted waters.

Vertical distribution of this parameter at the beginning of the research revealed no characteristic increase in the monimolimnion. An obvious increase was noted only in the deepest water layer (2-m thick) and was best observable in November 1996. In the final years, stratification of the conductivity was evident (and high concentration gradients of all examined chemical compounds), confirming a chemocline occurrence between 14 and 15 m depth.

The quantity of ions increasing along with the increasing depth is the reason for the water density changes, irrespective of the temperature. In the monimolimnion typical is the high content of dissolved gases and mineral compounds. They are characteristic for high density and even if the surface layers are considerably cooler homothermy does not occur and the density caused by the chemical factors becomes an obstacle for the settling and theoretically heavier water [14]. Conductivity in a stable monimolimnion may be about 3 times higher than in the other layers [3]. Lange [9] reported that conductivity distribution has practically no effect on the density stratification and therefore in the freshwater (characteristic for the generally low internal mineralization) studies, with sufficient accuracy, density can be considered a function of temperature. However, the studies of meromictic lakes have shown that thermal stability of water is to a large extent enhanced by chemical stability [22] which can be regarded as both the effect and the reason for the difficulty in water circulation. In the discussed case, there is only scarce information available regarding this parameter in the early phase of the research. In 1996, before the sequent shore collapse and the resultant depth reduction, in the layer below 15 m depth the values ranged from 502 to 807 $\mu S\cdot cm^{-1}$. Such values allowed for classifying the lake as high-conductivity reservoir [7].

Table 2. Variability ranges of the selected chemical parameters of the Lake Zapadłe waters at the start and at the end of the research

Depth [m]	Parameter [unit]	1990–1993	2005–2006
1	BOD_5	1.02–18.7	1.9–3.4
10	[mg $O_2\cdot dm^{-3}$]	1.0–15.9	1.3–2.6
15		11.0–24.6	4.0–5.1
17		16.4–42.4	7.5–8.1
20		21.4–53.8	
1	COD-Mn	6.1–14.9	4.6–7.4
10	[mg $O_2\cdot dm^{-3}$]	6.1–12.5	4.8–9.0
15		7.5–21.1	7.4–12.2
17		9.6–16.8	10.1–12.8
20		10.6–25.6	
1	Mineral phosphorus	0.01–0.627	0.039–0.353
10	[mg $P\cdot dm^{-3}$]	0.248–0.759	0.329–0.576
15		0.581–1.139	0.570–1.125
17		0.772–1.427	0.623–1.894
20		0.594–1.706	
1	Total phosphorus	0.023–0.643	0.147–0.420
10	[mg $P\cdot dm^{-3}$]	0.297–0.789	0.441–1.303
15		0.676–1.725	1.206–1.498
17		0.894–1.597	1.297–1.967
20		1.161–2.178	
1	Ammonium nitrogen	0.00–0.86	0.00–0.58
10	[mg $N\text{-}NH_4\cdot dm^{-3}$]	0.41–1.6	0.005–0.85
15		0.94–5.29	1.23–4.03
17		2.09–6.66	1.51–5.99
20		3.53–12.18	
1	Nitrate(V) nitrogen	no data	0.005–0.247
10	[mg $N\cdot dm^{-3}$]	0.00–0.12	0.142–0.146
15		0.00–0.35	0.006–0.183
17		0.11–0.31	0.028–0.071
20		0.00–0.45	

A vertical profile with an increase of the values in the metalimnion, like in the discussed case, is typical for fertile lakes. Fertility of a lake can be assessed on the ground of the content of nutrients: nitrogen and most of all – phosphorus. Anaerobic conditions in the deepest layers of Lake Zapadłe (Fig. 2) stimulated phosphorus release from the bottom sediments [12]. Wiśniewski and Planter [23] reported that phosphorus released from the bottom sediments in winter is not precipitated during the spring turnover and almost completely feeds the summer epilimnion thus contributing to the primary production development during the vegetative period. An example is the high-significance relationship between the circulating phosphorus content and the visibility and the chlorophyll a concentration during the summer stagnation observed in many lakes, including the meromictic Lake Starodworskie [17].

Phosphorus is the limiting element when $P/N \leq 20$. In Lake Zapadłe the value was approximately 3. According to Chełmicki [1], the concentration higher than 0.005 mg $P \cdot dm^{-3}$ accelerates the development of algae. Intensive phosphorus uptake by plants occurs in parallel with the favorable abiotic conditions, like light and temperature. In the discussed lake such situation was observed in the last study years, from May to November, when the average concentration of this ion down to 10 m depth equaled 0.281 mg $P \cdot dm^{-3}$ [15] and was lower than 0.317 mg $P \cdot dm^{-3}$ measured at the start of the research (1991–1993). In the surface water layers mineral phosphorus was present throughout the whole study reaching the maximum levels in the early 1990s (0.297–0.627 mg $P \cdot dm^{-3}$).

With regard to mineral nitrogen forms, the highest measured concentrations were of the ammonium nitrogen. Like in the case of other components, its vertical stratification was obvious and the considerable increase of the concentration occurred below 14 m depth. It proves that organic matter accumulates in this water layer [18] and undergoes anaerobic decomposition. Kracht [8] explained the increase of ammonium nitrogen by its additional release from the oxygen-free bottom sediments, such as the conditions observed in the deepest waters throughout the research. According to Chełmicki [1] ammonium nitrogen can also enter the lake directly from the drainage basin. Its absence or small amounts detected in the mixolimnion reflect good oxygenation of this water layer, as confirmed by nitrate(V) nitrogen content. Occurrence of nitrate(V) nitrogen in the surface layers is an effect of the nitrification, contributing to the utilization of carbon dioxide and to alkalinity reduction. It may also be caused by the nitrogen pollution from soil fertilization in the drainage basin [3, 21] or come from the nearby Lake Isąg through water filtration.

CONCLUSIONS

The conducted observations have revealed stabilization of the meromixis qualities in Lake Zapadłe.

High temperature gradients at the epi/metalimnion interface hinder circulation of the lake water. Thickness of the epilimnion has been clearly reduced over the study period.

Vertical distribution of temperature and conductivity indicates the setting of a monimolimnion below 13 m depth. The high chemical gradients between 14 and 15 m depth are the evidence for a chemocline occurrence at this depth.

Throughout the study, the conductivity and mineral nitrogen have decreased in the deepest water layers whereas phosphorus concentrations increased.

Water deoxygenation in the winter and the values of organic matter parameters are a sign of the high fertility of the lake.

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OBSERWACJE ZMIAN WYBRANYCH SKŁADNIKÓW CHEMICZNYCH WÓD MEROMIKTYCZNEGO JEZIORA ZAPADŁEGO W LATACH 1991–1994, 2000–2001 I 2005–2006

Badaniami objęto niewielkie (4,6 ha) jezioro meromiktyczne, położone w silnym zagłębieniu terenu i otoczone skarpą o znacznym nachyleniu. Na skutek zawalenia się brzegów zbiornik ten dwukrotnie uległ spłyceniu (z 20 do 18 m). Jest on zasilany wodami podziemnymi, posiada także stosunkowo stały odpływ. Ograniczona dynamika wód skutkowała spłyceniem warstwy epilimnionu (z 4 do 2 m), wytworzeniem monimolimnionu poniżej 13 m głębokości z charakterystycznym niewielkim (0,2° C) wzrostem temperatury w profilu pionowym oraz stałym odtlenieniem wód poniżej 7–11 m. Stosunek wskaźników materii organicznej (BZT_5 i ChZT-Mn) przed zawaleniem brzegów jeziora świadczy przewadze materii produkowanej w zbiorniku, w ostatnim okresie obserwowano sytuację odwrotną. W monimolimnione nastąpiło nagromadzenie materii allochtonicznej, a jej beztlenowy rozkład powodował powstawanie znacznych ilości amoniaku. Stwierdzono także spadek wartości przewodnictwa elektrolitycznego w tej partii wód.