Carpathian Journal of Earth and Environmental Sciences, February 2018, Vol. 13, No. 1, p. 5 – 13; DOI:10.26471/cjees/2018/013/001

# PARTICULAR EXAMPLE OF MEROMIXIS IN THE ANTHROPOGENIC RESERVOIR

**Jacek KUBIAK[1], Sylwia MACHULA[1] & Adam CHOIŃSKI[2]**

[1]*West Pomeranian University of Technology in Szczecin Department of Hydrochemistry and Aquatic Biological Resources Kazimierza Królewicza 4, 71-550 Szczecin, Poland, e-mail: jacek.kubiak@zut.edu.pl; sylwia.machula@zut.edu.pl, phone: +48 91 449 66 95; +48 91 449 66 98*

[2] *Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University Dzięgielowa 27, 61-680 Poznań, -mail: choinski@amu.edu.pl, phone: +48 (0)61 829 6260*

**Abstract:** The thermal regime of the Czarnogłowy, a post-mining lake studied in 2008-2010, showed the reservoir to be meromictic. Throughout the year, the water column of the lake was divided into two layers (the mixolimnion extending down to 20 m depth and the monimolimnion) separated by a distinct, thin (about 2.0 m thick) chemocline. The chemical composition of the mixolimnion water was highly variable, the highest concentrations being shown by Ca, Na, Cl, $SO_4$, and $HCO_3$ ions. The same ions were also dominant in the monimolimnion, but their concentrations there were much higher and much less variable. The Czarnogłowy meromixis was found to be crenogenic. The lake received an inflow of groundwater from springs in the reservoir and the elevated mineralisation may have resulted from the inflow of groundwater seeping through the sedimentary limestone in the catchment. However, due to the limited data, these findings need further investigation.

**Key words:** lake, meromixis, crenogenic meromixis, water thermal regime

## 1. INTRODUCTION

Post-mining reservoirs are used for recreation, tourism, and water retention; they may affect the local climate. The number of such reservoirs has been observed to increase (Krüger et al., 2002). They form a new category of man-made water bodies which play an important role in the structure and functioning of anthropogenically altered landscapes. Chemical conditions in these reservoirs are shaped primarily by the catchment lithology and by waters that feed them (Galas, 2003). On account of steeply sloping bottoms of such basins, their considerable depth, and the mineral-rich groundwater influx, post-mining reservoirs tend to be meromictic (Lyons et al., 1994; Rücker et al., 1999, Castro & Moore, 2000). Meromixis in post-mining reservoirs has been described by numerous authors who showed this type of mixing, as well as the ensuing stratification, to be enhanced by certain characteristics of those water bodies (Boehrer & Schultze, 2006).

The number of water bodies regarded as meromictic has been growing steadily. Findenegg (1937) was the first to define meromictic lakes as those that are chemically stratified and show incomplete circulation; he termed the stagnant layer as monimolimnion. The mixed layer was called the mixolimnion by Hutchinson (1937), the intermediate layer constituting the chemocline. The typology of meromictic layer proposed by Hutchinson (1937) was based on the causes underlying the meromictic structure of the water column. The first list of meromictic lakes, published by Yoshimura (1937), comprised 44 reservoirs, mainly in Japan and Europe. Extending Hutchinson's concept, Walker & Likens (1975) divided meromixis into exogenic (driven by extraneous forces) and endogenic (produced by factors intrinsic in a lake). The list compiled by Walker & Likens (1975) contained 121 meromictic reservoirs worldwide. In North America, Anderson et al., (1985) identified approximately 100 lakes which already are, or are likely to be, meromictic. Intensive studies of meromictic reservoirs have been conducted in Scandinavia, particularly in Norway (Hakala, 2004), who proposed a classification of meromictic lakes based on the major factor producing the meromictic structure of the water column. He distinguished between four types of meromixis: (1) driven by an inflow of saline water to a fresh water body (or by an influx of fresh water into a saltwater reservoir); (2) produced by a spatially significant input of nutrients; (3) originating as a result of upwelling of saline groundwater; (4) due to incomplete mixing of a lake resulting from its morphology.

The typology of natural meromictic lakes is applied also to post-mining reservoirs, described in many publications. Such areas have properties enhancing meromixis; in particular, they frequently show incursions of saline groundwater (Boehrer & Schultze, 2006). The emergence of meromictic structure in post-mining reservoirs is doubtless influenced, although to a lesser extent than in natural lakes, by their particular morphometry: generally, they are relatively deep and have small surface areas (Donachie et al., 1999).

In Poland, only a few lakes have been referred to as meromictic; these are: Zapadłe (Teodorowicz et al., 2003, Tandyrak et al., 2010), Czarne (Kraska et al., 2006), Rzeźnik (Zachwieja, 1970), Klasztorne Małe (Januszkiewicz, 1969), Wądołek (Czeczuga, 1966), Starodworskie (Tandyrak et al., 2009), Zakrzówek (Galas, 2003), and Gliniok (Molenda, 2011, 2013). This study was aimed at characterising Lake Czarnogłowy, a post-mining meromictic reservoir, and at identifying the causes of meromixis.

In this paper, an analysis of the water conductance, total dissolved salts (TDS) contents, and concentrations of major macroions was also carried out. For methodology see the analysis the seasonal changes of the temperature, pH and dissolved oxygen in the Cuejdel Lake, the largest natural barrage water body in Romania and the most recent natural dam lake in Europe, carried out by Mihu-Pintilie & Stoleriu, (2014).

## 2. MATERIALS AND METHODS

### 2.1. Area of study

The Czarnogłowy lake (53°45’24” N; 14°55’26” E; 24 m a.s.l.), located in the Szczecin Lowland, emerged as a result of inundation of a marlstone pit mine. Carboniferous rocks, a major feature of the geological setup of the area around the present-day reservoir, are amenable to commercial mining. The Upper Jurassic deposits occurring in the area are a part of a tectonic unit known as the Czarnogłowy anticline. It forms the north-western section of the Pomeranian anticlinorium, an area geologically unique on the scale of the entire European Lowland, with outcrops of sedimentary rocks (marl and limestone) (Mikołajski, 1966). Limestone deposits had been mined in the area since 1759, the 1941 output exceeding 600,000 tons. Mining activities continued until the mine was inundated in 1945. In 1947, mining was resumed and continued until 1968, when the drainage pumps were shut down, the mine was flooded, and a post-mine reservoir emerged.

The Czarnogłowy lake occupies 35.7 ha; its maximum and relative depths are 28.8 m and 4.27%, respectively, the long axis of the lake trending NW-SE. The maximum length and width of the reservoir are 1150 and 330 m, respectively, the shoreline being 2850 m long. In the southern part of the lake, the bottom drops almost vertically. The Czarnogłowy bathymetry is shown in figure 1. South of the lake (54°46’08 N; 15°55’20 E), there is another former open pit mine, now flooded, smaller than the Czarnogłowy. This trough-like reservoir covers 7 ha; its shoreline is 2400 m long, the maximum length and maximum width being 1050 and 120 m, respectively. Its western part is shaped like an elongated (500 m long) embayment 10-30 m wide; the remaining part is 100-120 m wide. These parameters determine the possibility of meromixis. The maximum depth of the lake is 28.8 m (Fig.1).

The immediate catchment area of the Czarnogłowy lake is forested. Although the water budget of the lake has not been put together, the lake is known to be periodically fed by a tributary in the east (Fig. 1). When the mine was in operation, the pit featured three springs. Their water was pumped into the nearby Wołczenica, a river 52.1 km long, which drains 421 $km^2$ and has a mean flow rate of 0.21 $m^3 s^{-1}$ (Friedrich, 1989).

On account of the non-typical origins of the Czarnogłowy lake and its unique geological setup and amenity qualities, the lake belongs to the most interesting water bodies in the north-west of Poland. The reservoir owes its popularity to the very clean water and the diversity of its underwater landscapes: the bottom features remains of a flooded forest, some of the trees still protruding above the water surface. Data on the Czarnogłowy thermal regime, salinity, and concentrations of basic macroions, collected during two annual surveys, make it possible to analyse details of mixing processes in the lake and to identify the causes of the water column structure observed.

### 2.2. Methods

The Czarnogłowy was studied in 2008-2011. Water temperature, salinity, and conductance of the water column were measured, at 1 m intervals, along a vertical profile extending to the deepest spot of the lake; the measurements were taken with a portable HI 9828 multiparameter water quality meter (Hanna Instruments).

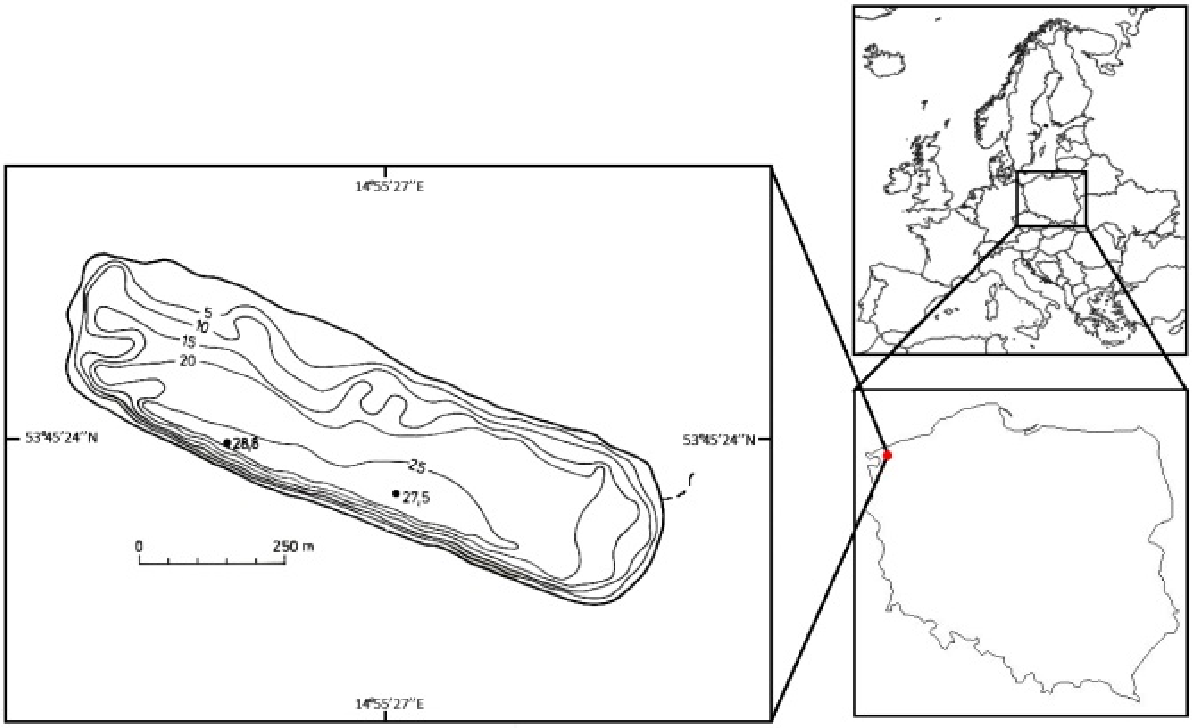


Figure 1. Geographical position and bathymetry of the Czarnogłowy Reservoir

In 2009 and 2010, water samples were collected for ion chromatography (carried out with the help of the Dionex 3000 device) assays of the following macroions: $SO_4^{-2}$, $Cl^-$, $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$. Alkalinity and carbonate content were determined by titration with 0.1 N HCl. The data were processed with the Statistica v. 9.0 software (StatSoft, Inc., 2009).

## 3. RESULTS

The Czarnogłowy water column showed a characteristic thermal stratification involving two layers. The upper layer, extending down to 19-20 m, showed a thermal cycle typical of holomictic lakes. Deeper in the water column (below 21-22 m), the temperature varied within a small range: 4.0-6.2, 4.0-6.4, 4.9-6.9, and 5.0-6.6°C in winter, spring, summer, and autumn, respectively. The temperature was usually observed to increase with depth to 25 m (particularly in the spring-summer period) and to remain stable from this level down to the bottom (Fig. 2). The steepest temperature gradient, observed at 21-22 m, amounted to 0.72, 0.64, 0.51, and 0.43°C $m^{-1}$ in winter, spring, summer, and autumn, respectively.

On the other hand, the upper layer showed a short winter stagnation (January and the first decade of February), spring mixing occurring until the third week of May. The summer conditions prevailed until the end of the first week of October, autumn conditions lasting until the last week of December (Fig. 2).

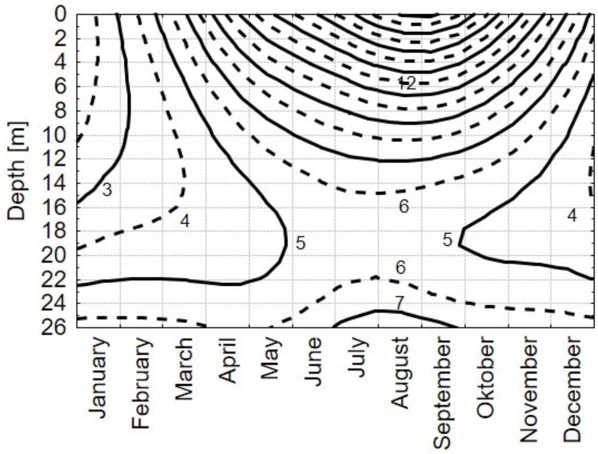


Figure 2. Thermal regime of the Czarnogłowy Reservoir water

The spring homothermy extended down to 20 m; the water temperature ranged from 4.1 to 4.3°C, the temperature gradient being slight only. The summer conditions were characterised by heterothermy developing in mid-August. The highest temperatures, with the maximum at 19.7°C, prevailed in the near-surface water from mid-July until the end of August (Fig. 3). The thermocline showed a sharp decrease (mean gradient of -2.5°C $m^{-1}$), the maximum gradient (-

5.8°C m$^{-1}$) occurring at the depth of 6.0 m. Below the thermocline, the water temperature in summer ranged from 7.8°C in the upper part of the sub-thermocline layer to 4.9°C in its lower part (Figs. 2, 3).

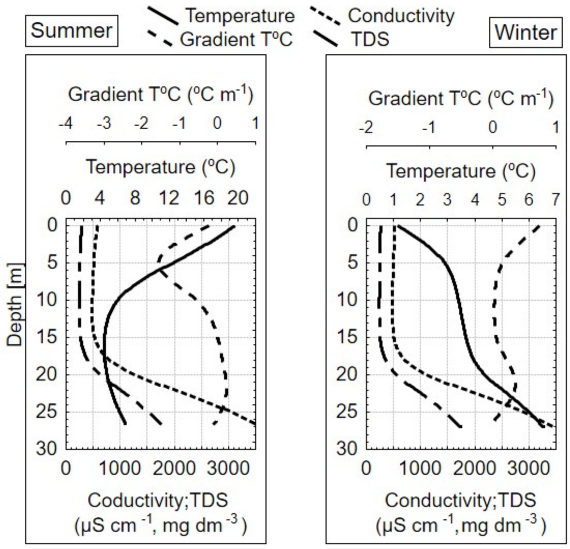


Figure 3. Temperature vs. salinity in the Czarnogłowy Reservoir water in summer and during the winter stagnation

The autumn homothermy (at 5.0°C) was observed in the mixolimnion of the Czarnogłowy lake at the end of the first decade of December (Fig. 3). In winter, the Czarnogłowy water column showed a typical inverse thermal stratification extending down to the depth of 20 m. The water temperature changed from 0.9-1.9°C at the surface to 3.0-3.3°C at the depth of 3 m; below that depth, the temperature gradually increased to 4°C at 20 m (Figs 2, 3).

The data on water conductance, total dissolved salts (TDS) contents, and concentrations of major macroions obtained confirmed the two-layer structure of the water column. The mixolimnion was, in all seasons, much less mineralised than the remaining part of the water column (Tables 1-4; Figs 4, 5), mineralisation indicators showing considerably smaller gradients. The maximum TDS content and conductance were 302.0 mg dm$^{-3}$ and 604.0 µS cm$^{-1}$, respectively (Table 3). The monimolimnion was set off by a distinct chemocline that started at 20-21 m where the TDS and conductance gradients averaged 115.9 mg dm$^{-3}$ m$^{-1}$ (maximum TDS of 920.0 mg) and 230.1 µS cm$^{-1}$ m$^{-1}$ (maximum conductance of 1709 µS cm$^{-1}$), respectively (Tables 1-4; Figs 3, 4).

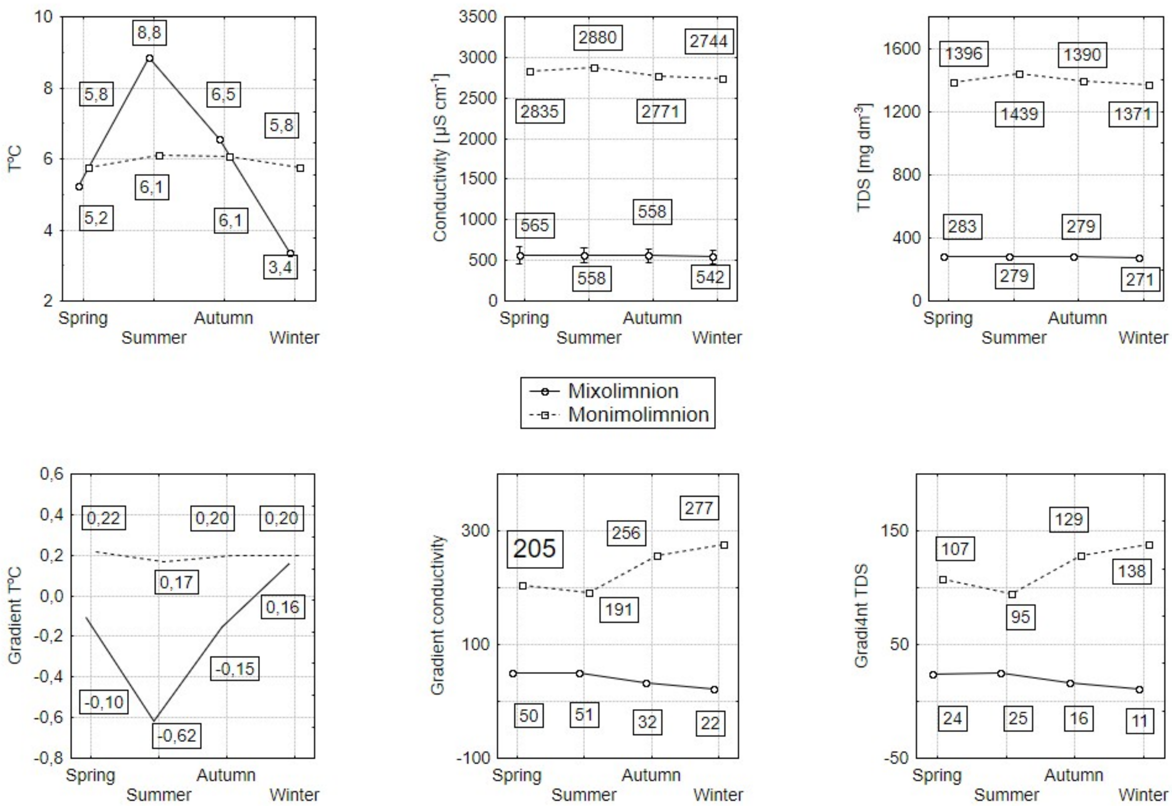


Figure 4. Average temperature (°C), conductance (µS/cm), salinity (TDS – mg/dm$^3$), and their gradients in the Czarnogłowy Reservoir mixolimnion and monimolimnion in different seasons

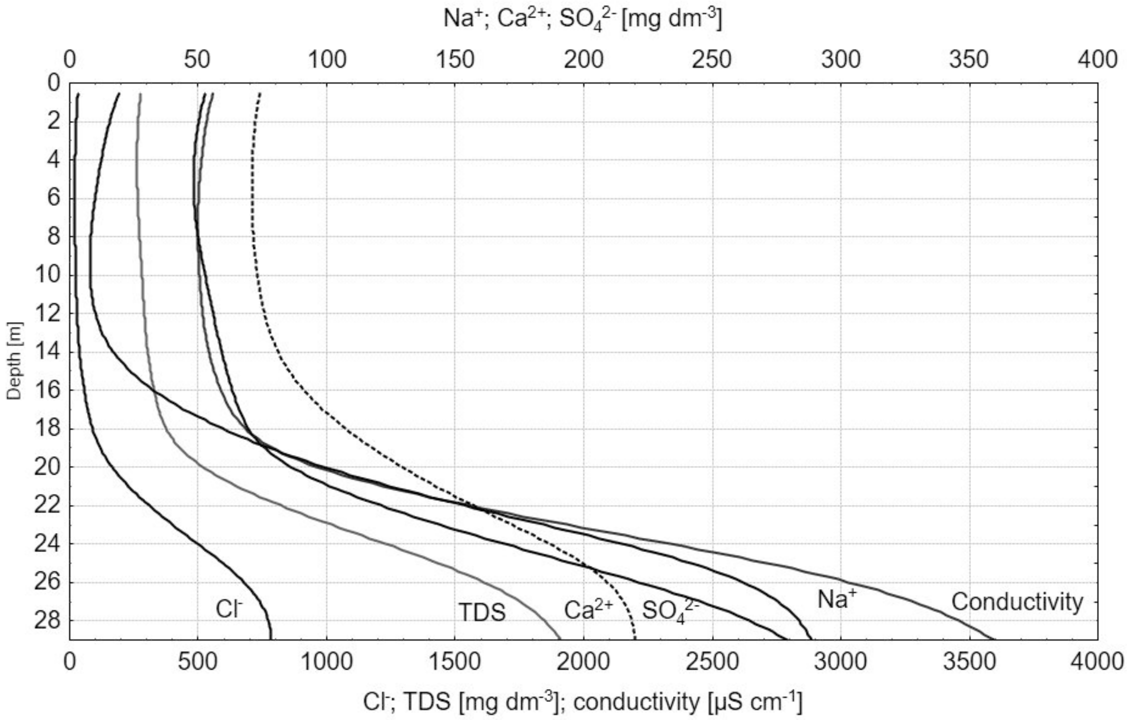


Figure 5. Changes with depth of the values of the studied indicators of water mineralization in Czarnogłowy Reservoir

Table 1. Temperature (°C) of the Czarnogłowy Reservoir water

| season | Layer | Indicator | Temperature (°C) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | Mean | Median | Minimum | Maximum | Range of maximum frequency |
| Spring | Mixolimnion | Value | 61 | 5.4 | 4.3 | 4.0 | 9.5 | 4.0-5.0 (63.9%) |
| | | Gradient | 61 | -0.10 | -0.03 | -1.24 | 0.24 | (-0.1) - 0.0; (56.3%) |
| | Monimolimnion | Value | 29 | 5.60 | 5.80 | 4.10 | 6.40 | 5.5 - 6.5 (66.7%) |
| | | Gradient | 26 | 0.25 | 0.16 | 0.00 | 0.64 | 0.1 - 0.2 (36.7%) |
| Summer | Epilimnion | Value | 9 | 18.4 | 18.9 | 15.8 | 19.7 | 18.5 - 19.5 (55.5%) |
| | | Gradient | 9 | -0.14 | -0.02 | -0.99 | -0.01 | (-0.2) - 0.0 (88.8%) |
| | Metalimnion | Value | 13 | 13.9 | 14.8 | 7.8 | 19.5 | 10.0 -16.0 (54.0%) |
| | | Gradient | 13 | -2.54 | -2.27 | -5.76 | -1.10 | (-2.0) - (-3.0) (40.0%) |
| | Hypolimnion | Value | 67 | 5.5 | 5.3 | 4.6 | 7.3 | 4.5 - 5.5 (35.8%) |
| | | Gradient | 64 | -0.01 | 0.00 | -0.94 | 0.97 | (-0.2) - 0.0 (33.3%) |
| | Mixolimnion | Value | 61 | 9.0 | 5.4 | 4.6 | 19.7 | 4.0 - 6.0 (58.7%) |
| | | Gradient | 61 | -0.65 | -0.09 | -5.76 | 0.09 | (-1.0) - 0.0 (63.5%) |
| | Monimolimnion | Value | 28 | 6.0 | 6.2 | 4.6 | 6.7 | 6.2 - 6.4 (40.0%) |
| | | Gradient | 25 | 0.20 | 0.18 | -0.59 | 0.72 | 0.0 - 0.2 (56.5%) |
| Autum | Mixolimnion | Value | 64 | 6.6 | 5.0 | 4.9 | 10.7 | 4.0 - 6.0 (67.7%) |
| | | Gradient | 64 | -0.06 | 0.00 | -2.47 | 0.12 | (-0.5) - (0.0) (66.2%) |
| | Monimolimnion | Value | 26 | 6.00 | 6.20 | 5.10 | 6.70 | 6.0 - 6.6 (48.0%) |
| | | Gradient | 23 | 0.20 | 0.21 | 0.01 | 0.43 | 0.2 - 0.3 (40.9%) |
| Winter | Mixolimnion | Value | 59 | 3.3 | 3.5 | 0.9 | 4.2 | 3.0 - 4.0 (80.0%) |
| | | Gradient | 59 | 0.15 | 0.06 | -0.21 | 1.35 | 0.0 - 0.2 (62.7%) |
| | Monimolimnion | Value | 27 | 5.7 | 6.1 | 4.1 | 6.2 | 6.0 - 6.5 (63.0%) |
| | | Gradient | 24 | 0.22 | 0.10 | -0.18 | 0.72 | (-0.2) - 0.0 (50.0%) |
| Entire year | Mixolimnion | Value | 210 | 6.3 | 5.0 | 0.9 | 19.7 | 4.0 - 6.0 (67.7%) |
| | | Gradient | 210 | -0.22 | 0.00 | -5.76 | 1.35 | (-0.5) - (0.0) (66.2%) |
| | Monimolimnion | Value | 87 | 6.0 | 6.1 | 4.1 | 6.7 | 6.0 - 6.6 (48.0%) |
| | | Gradient | 77 | 0.20 | 0.18 | -0.59 | 0.72 | 0.2 - 0.3 (40.9%) |

Table 2. Conductivity (µS/cm) of the Czarnogłowy Reservoir water

| season | Layer | Indicator | Conductivity (µS/cm) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | Mean | Median | Minimum | Maximum | Range of maximum frequency |
| Spring | Mixolimnion | Value | 61 | 557.6 | 554.0 | 540.0 | 603.0 | 540 - 560 (52.3%) |
| | | Gradient | 61 | 13.00 | 1.00 | -1.50 | 92.00 | 0-20 (67.2%) |
| | Monimolimnion | Value | 29 | 2541.0 | 3043.0 | 571.0 | 3272.0 | 3000-3500 (57.6%) |
| | | Gradient | 26 | 290.4 | 46.7 | -5.8 | 1371.0 | 0-200 (46.7%) |
| Summer | Epilimnion | Value | 9 | 542.4 | 545.5 | 536.0 | 554.0 | 535. -540 (55.5%) |
| | | Gradient | 9 | 0.44 | 1.00 | 2.00 | 2.00 | 0.5 - 1.0 (44.4%) |
| | Metalimnion | Value | 13 | 533.1 | 552.0 | 539.0 | 557.0 | 550 - 560 (46.2%) |
| | | Gradient | 13 | 3.92 | 2.00 | 0.00 | 21.00 | 0 - 5 (76.9%) |
| | Hypolimnion | Value | 67 | 1457.8 | 567.0 | 553.0 | 3200.2 | 500 - 1000 (62.7%) |
| | | Gradient | 64 | 120.7 | 2.0 | -576.0 | 2317.0 | 0 - 250 (37.6%) |
| | Mixolimnion | Value | 61 | 558.2 | 560.0 | 536.0 | 599.0 | 550 - 570 (76.1%) |
| | | Gradient | 61 | 4.27 | 1.00 | -5.00 | 159.00 | 0 - 100 (60.2%) |
| | Monimolimnion | Value | 28 | 2703.3 | 30.84.0 | 566.0 | 3200.2 | 3000 - 3500 (65.4%) |
| | | Gradient | 25 | 300.6 | 37.0 | -576.0 | 1317.0 | 0 - 250 (48.7%) |
| Autum | Mixolimnion | Value | 64 | 555.8 | 552.5 | 522.0 | 604.0 | 540 580 (55.4%) |
| | | Gradient | 64 | 6.47 | 1.00 | -3.00 | 106.00 | 0 - 20 (68.8%) |
| | Monimolimnion | Value | 26 | 2691.0 | 3024.6 | 631.0 | 3269.0 | 3000 - 3500 (54.2%) |
| | | Gradient | 23 | 318.1 | 33.0 | -679.0 | 1709.0 | 0 - 500 (57.1%) |
| Winter | Mixolimnion | Value | 59 | 524.4 | 546.0 | 450.0 | 571.0 | 540 - 560 (86.4%) |
| | | Gradient | 59 | 21.90 | 0.00 | -3.00 | 328.00 | (-10) - (0) (69.6%) |
| | Monimolimnion | Value | 27 | 2743.9 | 3098.0 | 899.0 | 3128.0 | 3000 - 3500 (66.7%) |
| | | Gradient | 24 | 276.8 | 9.6 | -26.0 | 1358.0 | 0 - 200 (45.5%) |
| Entire year | Mixolimnion | Value | 210 | 556.8 | 554.0 | 450.0 | 604.0 | 550 - 600 (58.1%) |
| | | Gradient | 210 | 6.00 | 1.00 | -5.00 | 159.00 | 0 - 50 (59.3%) |
| | Monimolimnion | Value | 87 | 2811.8 | 3091.0 | 566.0 | 3272.0 | 3000 - 3500 (54.2%) |
| | | Gradient | 77 | 230.1 | 1.6 | -679.0 | 1709.0 | 0 - 500 (57.1%) |

The hydrocarbonate content in the mixolimnion averaged 3.5 mval dm$^{-3}$; the average contents of sulphates, chlorides, sodium, and calcium were 42.2, 39.6, 23.4, and 81.1 mg dm$^{-3}$, respectively (Table 4). Relatively large positive values of kurtosis obtained for Cl (11.4), Na (15.7), Mg (12.0) and Ca (13.7) prove that in these cases most observations are concentrated close to the mean and their variations are small (Table 4). This proves that the mixolimnion waters are not influenced by factors that may affect the concentration of these ions, as for example dilution by the surface water inflow and precipitation or mixing with the bottom waters of the monimolimnion. However, it has to be noted that due to the limited data availability some of the analysed populations are small, thus the obtained results need further investigation.

The monimolimnion, i.e., the layer below 21 m, was distinctly mineralised, the macro-ion concentrations being much less variable than those in the overlying layer (Tables 1-4; Fig. 5). The TDS content and conductance average 1400.1 mg dm$^{-3}$ and 2811.8 µS cm$^{-1}$, respectively. Hydrocarbonates, chlorides, and sulphates were still the dominant anions; the dominant cations – sodium and calcium – occur at concentrations much higher than in the overlying layer. Chloride and calcium ions occurred at concentrations averaging 691.8 and 216.7 mg dm$^{-3}$, respectively, hydrocarbonate concentrations averaging 8.2 mval dm$^{-3}$ (Table 4).

The steepest gradients of temperature and chemical indicators were recorded at the depth of 20-21 m where conductance and TDS changed, on average, by 1476.0 µS cm$^{-1}$ and 11450 mg dm$^{-3}$, respectively. Below this layer, the gradients were substantially less steep. Thus, the chemocline is very sharp and occur basically within a 2-m thick layer.

Table 3. Total dissolved salts (TDS) ($mg/dm^3$) contents of the Czarnogłowy Reservoir water

| season | Layer | Indicator | Total dissolved salts ($mg/dm^3$) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N | Mean | Median | Minimum | Maximum | Range of maximum frequency |
| Spring | Mixolimnion | Value | 61 | 278.7 | 277.0 | 255.2 | 302.0 | 270-285 (68.7%) |
| | | Gradient | 61 | 1.57 | 1.00 | -1.00 | 45.00 | 0 - 0.2 (53.3%) |
| | Monimolimnion | Value | 29 | 1233.8 | 1523.1 | 286.0 | 1636.0 | 1400-1700 (49.4%) |
| | | Gradient | 26 | 146.9 | 64.0 | -10.0 | 686.0 | 0 - 100 (43.3%) |
| Summer | Epilimnion | Value | 9 | 271.2 | 273.0 | 268.0 | 277.0 | 268 -270 (44.4%) |
| | | Gradient | 9 | 0.11 | 0.00 | -1.00 | 1.00 | (-0.5) - 0.0 (66.7%) |
| | Metalimnion | Value | 13 | 276.5 | 276.0 | 269.0 | 283.0 | 272 - 280 (69.2%) |
| | | Gradient | 13 | 2.0 | 1.0 | 0.0 | 11.0 | 0 - 2 (76.9%) |
| | Hypolimnion | Value | 67 | 728.7 | 284.0 | 277.0 | 1602.0 | 300 - 400 (48.1%) |
| | | Gradient | 64 | 59.1 | 1.0 | -288.0 | 1158.0 | 0-100 (36.6%) |
| | Mixolimnion | Value | 61 | 279.1 | 280.0 | 268.0 | 300.0 | 275 - 285 (76.8%) |
| | | Gradient | 61 | 2.15 | 0.00 | -2.00 | 79.00 | (-2.0) - 2.0 (90%) |
| | Monimolimnion | Value | 28 | 1351.0 | 154.1 | 283.0 | 1602.0 | 1400-1600 (76.9%) |
| | | Gradient | 25 | 143.8 | 13.0 | -288.0 | 920.0 | 0-200 (58.3%) |
| Autumn | Mixolimnion | Value | 64 | 277.9 | 276.0 | 261.0 | 302.0 | 280 - 295 (42.1%) |
| | | Gradient | 64 | 3.25 | 1.00 | -1.00 | 53.00 | 0 - 10 (57.8) |
| | Monimolimnion | Value | 26 | 1349.6 | 1512.4 | 316.0 | 1667.0 | 1400 - 1600 (50.0%) |
| | | Gradient | 23 | 159.6 | 22.3 | -339.0 | 855.0 | 0 - 200 (47.6%) |
| Winter | Mixolimnion | Value | 59 | 271.2 | 273.0 | 225.0 | 286.0 | 270 - 280 (86.4%) |
| | | Gradient | 59 | 10.9 | 0.0 | -2.0 | 163.0 | (-5.0) - 0.0 (75.0%) |
| | Monimolimnion | Value | 27 | 1371.1 | 1549.0 | 449.0 | 1564.0 | 1400 - 1600 (77.8%) |
| | | Gradient | 24 | 138.5 | 3.1 | -14.0 | 679.0 | 0 - 200 (50.0%) |
| Entire year | Mixolimnion | Value | 210 | 278.4 | 277.0 | 225.0 | 302.0 | 260 - 280 (57.1) |
| | | Gradient | 210 | 6.6 | 1.0 | -2.0 | 163.0 | 0 - 20 (49.3%) |
| | Monimolimnion | Value | 87 | 1400.1 | 1548.0 | 283.0 | 1667.0 | 1400 - 1600 (50.0%) |
| | | Gradient | 77 | 115.9 | 8.0 | -339.0 | 920.0 | 0 - 200 (47.6%) |

Table 4. Mineralisation indicators ($mg/dm^3$) of the Czarnogłowy water in 2009-2010; selected statistics

| Layer | Indicator | N | Mean | Median | Minimum | Maximum | Standard deviation | Coefficient of varia-tion | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|---|---|
| Mixolimnion | $HCO_3^{-1}$ | 72 | 3.5 | 3.4 | 2.8 | 5.0 | 0.5 | 13.8 | 0.8 | 0.2 |
| | $SO_4^{2-}$ | 72 | 42.2 | 40.0 | 20.7 | 89.5 | 13.0 | 30.7 | 1.2 | 2.1 |
| | Cl- | 72 | 39.6 | 28.4 | 22.1 | 199.4 | 31.0 | 78.1 | 3.2 | 11.4 |
| | Na | 16 | 23.4 | 14.5 | 9.0 | 156.2 | 35.6 | 152.3 | 3.9 | 15.7 |
| | Mg | 16 | 11.3 | 10.2 | 8.5 | 26.3 | 4.3 | 37.8 | 3.3 | 12.0 |
| | K | 16 | 2.2 | 1.4 | 1.1 | 5.2 | 1.5 | 65.4 | 1.2 | -0.3 |
| | Ca | 16 | 81.1 | 73.4 | 66.1 | 180.2 | 27.3 | 33.6 | 3.6 | 13.7 |
| Monimolimnion | $HCO_3^{-1}$ | 17 | 8.2 | 8.7 | 5.5 | 11.7 | 0.64 | 7.8 | 0.3 | 1.2 |
| | $SO_4^{2-}$ | 17 | 224.1 | 189.0 | 134.5 | 388.2 | 17.0 | 7.6 | 0.8 | -0.8 |
| | Cl- | 17 | 691.8 | 704.1 | 466.4 | 1100.3 | 99.6 | 14.4 | 0.8 | 0.6 |
| | Na | 4 | 279.1 | 279.9 | 259.9 | 296.7 | 16.1 | 5.8 | -0.2 | -1.7 |
| | Mg | 4 | 43.0 | 43.1 | 40.4 | 45.4 | 2.1 | 4.9 | -0.2 | -0.8 |
| | K | 4 | 3.1 | 3.1 | 2.8 | 3.3 | 0.2 | 7.9 | -0.1 | -3.4 |
| | Ca | 4 | 216.7 | 216.8 | 197.1 | 236.1 | 16.7 | 7.7 | 0.0 | -1.0 |

## 4. DISCUSSION

The thermal regime of the Czarnogłowy water column was unequivocally typical of meromixis, as it was described by Findenegg (1937), Hutchinson (1937), Kalff (2002) and Wetzel (2001). There were three characteristic layers: the stagnant monimolimnion, the well-mixed mixolimnion, and the chemocline with sharp gradients of temperature and mineralisation indicators. The mixolimnion and monimolimnion differ in TSD by an average of over 1000 mg $dm^{-3}$ (Figs 1, 2), a TDS increase by 10 mg $dm^{-3}$ causing a density increase identical to that brought about by a temperature reduction from 5 to 4°C (Lampert & Sommer, 2007). Thus, even if the surface layer cools significantly, the water column would not be fully mixed.

The cause of meromixis in the Czarnogłowy was revealed during the analysis of mineralisation of the reservoir's water column. The disused pit mine received an inflow of groundwater from three springs in the reservoir. Thus, the groundwater remains subsequently in constant contact with the water column. The chemical composition of the groundwater is affected by leaching of the catchment rocks (Humnicki, 2006), the groundwater being drained via the surface flow (River Wołczenica). Analyses of the macro-ion concentrations in the monimolimnion demonstrated the distinctly elevated mineralisation may have resulted from the inflow of groundwater seeping through the sedimentary limestone present in the catchment. The limestone's origin dates back to the sea present in the area in the Jurassic (Mikołajski, 1966), for which reason the monimolimnion water chemistry is dominated by calcium and sodium (cations) as well as by hydrocarbonates, chlorides, and sulphates (anions). Chemistry of water overlying sedimentary rocks is shaped by the solubility and composition of the rock-forming minerals. Sodium and chloride ions are characteristic of saline sedimentary rocks; sulphates often accompany sedimentary rocks, whereas calcium and hydrocarbonate ions are typical of groundwater occurring in limestone (Macioszczyk & Dobrzyński, 2002). This conclusion is in agreement with Boehrer & Schultze (2006) who stated that water chemistry of post-mining reservoirs depends primarily on the catchment lithology (mine type) and the source of water feeding the reservoir (precipitation, underground infiltration, surface waters).

As the Czarnogłowy is fed by highly saline groundwater, surface waters, and precipitation, the last two of a low mineral content, the water column shows a stratification pattern typical of meromixis. Moreover, on account of the lake being fed by highly mineralised groundwater, the meromixis in the Czarnogłowy can be regarded as crenogenic (Hutchinson, 1937). The meromixis occurring as a result of human activity is also known as anthropogenic meromixis (Kalff, 2002). A similar system was observed in the former lignite mine in Merseburg (Germany) with saline groundwater entering the reservoir at a large depth, the inflow being facilitated by the drainage of the mining pit effected when the mine was operational (Schreck, 1998).

Considering the location of the Czarnogłowy relative to the sea and the origins of the reservoir, neither seawater seepage nor salt release due to organic matter decomposition seem to be plausible mechanisms responsible for salt accumulation in the monimolimnion.

## REFERENCES

**Anderson, R.Y., Dean, W.E., Bradbury J.P. & Love, D.** 1985. *Meromictic lakes and varied lake sediments in North America*. U.S. Geol. Surv. Bull. 1607, 1-19.

**Boehrer, B. & Schultze, M.** 2006. *On the relevance of meromixis in mine pit*. Proceed. of 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation. 3134 Montavesta Road, Lexington, KY 40502: ASMR.

**Castro, J.M. & Moore, J.N.** 2000. *Pit lakes: their characteristics and the potential for their remediation*. Environ. Geol. 39, 1254-1260.

**Czeczuga, B.** 1966. *Wądołek – a holomictic lake*. Acta Hydrobiol. 8(1), 1-4.

**Donachie, S.P., Kinzie, A.R., Bidigare, R.R., Sadler, D.W. & Karl, D.M.** 1999. *Lake Kauhako, Moloka'I, Hawa'I: biological and chemical aspects of morpho-tectogenic meromictic lake.* Aquatic Microbial Ecology, 19, 93-103.

**Findenegg, I.** 1937. *Holomiktische und meromiktische Seen*. Int. Rev. ges. Hydrobiol. 35, 586-610.

**Friedrich, M.** 1989. *Low mean flow rates in selected rivers in the Szczecin Voivodeship. Słupsk:* Institute of Meteorology and Water Management. Słupsk Branch. Department of Regional Studies, typescript.

**Galas, J.** 2003. *Limnological study on a lake formed in a limestone quarry (Kraków, Poland).* Polish J. Environmental Stud. 12(3), 297-300.

**Hakala, A.** 2004. *Meromixis as a part of lake evolution; observations and a revised classification of true meromictic lakes in Finland*. Boreal Wnv. Res. 9, 37-53.

**Humnicki, W.** 2006. *Groundwater feeding and drainage (In:) Basics of applied hydrogeology.* Ed.

Macioszczyk A. Wyd. Nauk. PWN, Warszawa, 80-89. (in Polish)

**Hutchinson, G.E.** 1937. *A contribution to the limnology of arid regions*. Trans. Conn. Acad. Arts Sci. 33, 47-132.

**Januszkiewicz, T.** 1969. *Studies of Lake Klasztorne as a sewage receptacle*. Water Management, 3, 43-81.

**Kalff, J.** 2002. *Limnology*. New Jersey: Prentice Hall Ltd.

**Kraska, M., Klimaszyk, P. & Piotrowicz, R.** 2006. *Meromictic Lake Czarne in the Drawienski National Park.* Oceanological and Hydrobiological Studies XXXV, 1, 55-67. DOI: 10.2478/v10009-010-0048-y.

**Krüger, B., Kadler, A. & Fischer, M.** 2002. *The Creation of Post-Mining Landscapes of Lignite Mining in the New Federal States.* Surface Mining - Braunkohle and other minerals. 54, 161- 169.

**Lampert, W. & Sommer, U.** 2007. *Limnoecology. The ecology of lakes and streams.* New York: Oxford Univ. Press. Inc.

**Lyons, W.B., Doyle, G.A., Petersen, R.C. & Swanson, E.E.** 1994. *The limnology of future pit lakes in Nevada: The importance of shape.* In: Tailings and Mine Waste '94 (pp. 245-248). Balkema, Rotterdam.

**Macioszczyk, A. & Dobrzyński, D.** 2002. *Hydrogeochemistry. Zones of the acitve change of groundwater.* Wyd. Nauk. PWN, Warszawa, 448pp

**Mihu-Pintilie A. Stoleriu C.,** 2014. *The seasonal changes of the temperature, pH and dissolved oxygen in the Cuejdel Lake, Romania.* Carpathian Journal of Earth and Environment, 9(2):113-123.

**Mikołajski, J.** 1966. *Geography of the Szczecin Voivodeship.* Pr. Szczec. Tow. Nauk. 12: 1-156.

**Molenda T.,** 2011. *Natural and anthropogenic factors of changes of physical-chemical properties of waters in post-mining aquatic environments. An example of the Upper Silesia region and the neighbouring areas.* Wyd. Gnome. Katowice.

**Molenda T.,** 2013. *Impact of the drainage of saline mining water on the development of a meromictic pit reservoir (Gliniok/Poland)* (in printing)

**Rücker, J., Fyson, A., Deneke, R. & Packroff, G.** 1999. *Meromiktische Seen mit saurem Mixolimnion - eine Besonderheit der Lausitzer Bergbaufolgelandschaft.* In: DGL-Tagungsbericht 1998 (Klagenfurt) (pp. 239-243). Tutzing: Eigenverlag der DGL.

**Schreck, P.** 1998. *Environmental impact of uncontrolled waste disposal in mining and industrial areas in Central Germany*. Environ. Geol., 35, 66-72.

**StatSoft, Inc.** 2009. STATISTICA (data analysis software system), version 9.0. www.statsoft.com.

**Tandyrak, R., Paraszuto, K., Górniak, D. & Kośnik, P.** 2009. *Hydrochemical properties, bacterioplankton abundance and biomass in the meromictic Lake Starodworskie in 2004.* Oceanological and Hydrobiological Studies XXXVII, 4, 127-133.

**Tandyrak, R., Teodorowicz, M. & Grochowska, R.** 2010. *Observations of selected chemical components of meromictic Lake Zapadłe waters in 1990-1993, 2000-2001 and 2005-2006.* Archiv. Environmental Protection, 36(3), 75-82.

**Teodorowicz, M., Dunalska, J. & Górniak, D.** 2003. *Hydrochemical properties of a meromictic Lake Zapadłe.* Rev., 3, 249–254

**Walker, K.F. & Likens, G.E.** 1975. *Meromixis and a reconsidered typology of lake circulation patterns.* Verh. Intern. Verein. Limnol. 19, 442-458.

**Wetzel, R.G.** 2001. *Limnology. Lake and River Ecosystems.* London: Academic Press.

**Yoshimura, S.** 1937. *Abnormal thermal stratifications of inland lakes.* Proc. Imp. Acad. 13, 316-319.

**Zachwieja, J.** 1970. *Meromixis of Lake Rzeźniki in the mazurian lake district.* Ekologia Polska, 12(17), 273-290.

Received at: 18. 03. 2014
Revised at: 07. 05. 2017
Accepted for publication at: 24. 05. 2017
Published online at: 06. 06. 2017