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The unique environment of the most acidified permanently meromictic lake in the Czech Republic

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ABSTRACT

Changes in the water properties and biological characteristics of the highly acidic Hromnice Lake (Western Bohemia) were investigated. This 110-year-old lake, formed as a consequence of the mining of pyritic shales, is permanently meromictic. Two chemoclines separate an extremely acidic (pH ∼ 2.6) mixolimnion from a metal-rich anoxic monimolimnion. The absence of spring mixolimnetic turnover due to ice melting and very slow heat propagation through the chemocline with a 6-month delay were observed. Extreme mixolimnetic oxygen maxima (up to 31 mg l^{-1}) in phosphorus-rich lake (PO_4^{3-} up to 1.6 mg l^{-1}) well correlated with outbursts of phytoplankton. Phytoplankton consist of several acido-tolerant species of the genera *Coccomyxa*, *Lepocinclis*, *Chlamydomonas* and *Chromulina*. Surface phytoplankton biomass expressed as chlorophyll-*a* varies from 2 to 140 μg l^{-1}. Multicellular zooplankton are almost absent with the exception of *Cephalodella acidophila*, a small rotifer occurring in low numbers. Large red larvae of the midge *Chironomus* gr. *plumosus* were found at the bottom close to the shore, with larvulae in the open water. Developmental stages (protonemata) of a moss, resembling filamentous algae, dwell in the otherwise plant-free littoral zone.

Introduction

A few hundred anthropogenic lakes have formed in the Czech Republic due to the spontaneous flooding of abandoned mines after the termination of opencast mining (Hrdinka, 2007). These lakes often differ significantly from natural ones in morphometric and hydrological properties (Castendyk and Eary, 2009). Extreme examples are the lakes formed after the mining of pyritic shales. In the 19th century, this rock high in sulphides with an admixture of organic carbon (Pašava et al., 1996) was extracted and processed to obtain a supersaturated sulphuric acid (oleum) near Hromnice village. After the termination of mining in 1893, the pit was spontaneously flooded with acid rock drainage thus forming Hromnice Lake. In 1975, the area was declared a natural monument because of its unique status.

Studies of lakes formed after the mining of sulphidic ores with high pyrite content, are known from Spain (Sánchez España et al., 2008; Wendt-Potthoff et al., 2011), the USA (Pellicori et al., 2005), Greece (Triantafyllidis and Skarpelis, 2006), Sweden (Ramstedt et al., 2003), and Czech Republic (Hrdinka and Šobr, 2010). Similar properties have also been observed in lakes after the mining of hard coal and lignite in Germany (Geller et al., 1998; Schultze and Boehrer, 2008; Schultze et al., 2010; von Rohden et al., 2010), Austria (Moser and Weisse, 2011), and France (Denimal et al., 2005). The stratification of pit lakes and the phenomenon of meromixis have been studied *e.g.* by Boehrer and Schultze (2008), who also provided an overview of studies dealing with this topic (Boehrer and Schultze, 2006).

The specific properties of mining lakes waters are often evaluated from long-term perspectives. The aim of this study was to detail the yearly course of the basic physical and chemical properties of Hromnice Lake associated with the meromixis and to identify the processes involved therein. Further, we focused on identifying the organisms present in the lake adapted to extreme conditions and to compare the community of Lake Hromnice with communities of other extremely acidic lakes in Germany and Austria (Nixdorf et al., 1998a,b; Deneke, 2000; Lessmann et al., 2000; Wollmann et al., 2000; Moser and Weisse, 2011).

Because this unique environment has been developing for over 110 years, a comparison of the results with lakes of similar origin might bring new information as to how these specific ecosystems may evolve.

The sections on morphometry, physical and chemical limnology were written by T. Hrdinka and M. Šobr, the section on biology by J. Fott and L. Nedbalová.

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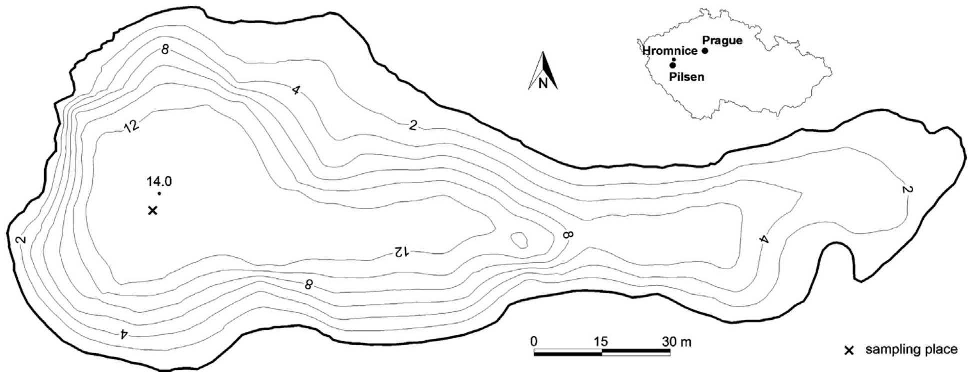

Fig. 1. Bathymetric map of Hromnice Lake (Hrdinka and Šobr, 2010) with the site of physical parameter measurements in the vertical profile and water sampling for chemical analysis marked, contour interval 2 m.

Study site and methods

Geological background and water regime

Hromnice Lake (49°51′02.5″ N, 13°26′39.3″ E) is located in the west of the Czech Republic at the bottom of an approx. 50 m deep mining pit with outer dimensions of 260 m × 150 m (Fig. 1). The lake surroundings are densely forested, with a large area of arable land to the north of the pit regularly slanting towards the lake. The geochemistry of the rock was studied by Pašava et al. (1996), who detected elevated concentrations of sulphur (av 1.61 wt%), organic carbon (av 0.68 wt%) and metals (av 4.15 Fe_{tot} wt%, 0.570 V wt‰, 0.383 Zn wt‰, 0.156 Cr wt‰, 0.093 Cu wt‰, 0.088 Ni wt‰) in a drill hole in close proximity to the site. The lake basin is formed by strongly inclined slopes formed by bare rock and unconsolidated shale debris. The presented morphometric characteristics (Table 1) show that the shape of the lake basin (relative depth, bottom inclination) and wind-protected lake position are factors that can contribute to the formation of permanent lake stratification (Miller et al., 1996; Doyle and Runnells, 1997).

To evaluate the water balance of the lake, which has no surface inlet or outlet, a Solinst 3001 Levelogger was used to record the air pressure compensated water level with an accuracy of 1 mm over a period of 1 year (September 2010–August 2011) at regular 1 h intervals. Further, meteorological data from the Plzeň-Mikulka weather station (mean daily air temperature) and Hromnice rain gauge (daily precipitation) were assessed (Czech Hydrometeorological Institute data). The results (Fig. 2) show a strong subsurface inflow, documented in the prominent increase of water level during the winter season (with relatively lower precipitation) and also a quick response of the water level to causal precipitation throughout the year. The water level fluctuation of 0.86 m during the observation period is equivalent to a lake volume change of 7714 m^3, *i.e.* 13% of the maximum. During the period from December 2010 to March 2011 the lake was permanently covered with ice.

Measurements and sampling

Measurements of the physical properties of the water and sampling for chemical and biological analysis were performed above the deepest point of the lake. Physical properties of water were measured with a YSI 6920 multi-parametric probe at approx. 2-week intervals from September 2010 to August 2011, using 0.25 m steps to a depth of 5 m and further 0.5 m steps down to the bottom. The YSI 6920 probe measures temperature with an accuracy of ±0.1 °C, conductivity with Ni-electrodes compensated to T = 25 °C (±10 μS cm^{-1}), dissolved oxygen with an amperometric (Clarke) electrode (±0.2 mg l^{-1}), pH with a glass electrode (±0.2 unit) and ORP as the potential between Pt and Ag/AgCl electrodes with an accuracy of ±20 mV (YSI Incorporated, 2009). Water transparency was determined under standard conditions using a Secchi disc (30 cm diameter), and water colour according to the Forel-Ule scale against a Secchi disc at half the transparency depth. The results were visualized using the Kriging interpolation method in Golden Software Surfer 8.

Water samples for chemical analysis were taken in the same time period at approx. 6-week intervals using a 2 L van Dorn sampler (integrating 0.5 m-high water columns) from three horizons at depths of 0.3 m, 5 m and 12 m (the layer approx. 1.5 m above the bottom, excluding the possibility of contamination by sediments). Major ions (Ca, Mg, Na, K, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, PO_4^{3-}), Fe(II) (bubble-free sample, trace metal grade HNO_3 acidified to pH < 1 on site), total organic carbon TOC (bubble-free sample), pH and selected metals (Fe, Al, Cu, Zn) were determined. Unfiltered samples were immediately transported to the laboratories of the T.G.M. Water Research Institute in Prague, where they were processed within 48 h, with the exception of pH and Fe(II), which were determined immediately. On the first sampling date, sulphidic sulphur S(-II) (sample stabilized with sodium ascorbate) and other metals (Mn, Ni, Cr, Co, Cd) were additionally determined.

Samples for the identification of phytoplankton and determination of chlorophyll-*a* were taken together with samples for chemical analysis using the same sampling technique. An additional sample of phytoplankton and chlorophyll was taken on

Table 1
Morphometric characteristics of Hromnice Lake.

Mean surface level (m a.m.s.l.)	330	Perimeter (m)	535
Area (m^2)	9740	Maximum depth (m)	14.0
Volume (m^3)	60,980	Mean depth (m)	6.3
Maximum length (m)	221	Relative depth (%)	12.2
Maximum width (m)	79	Mean slope of basin (°)	27

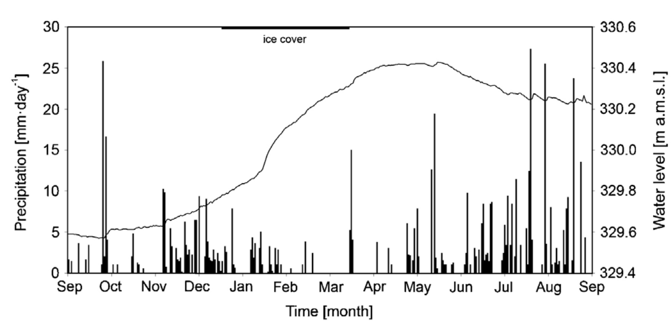

Fig. 2. Water level changes in Hromnice Lake (solid line) and daily precipitation (columns).