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The evolution of a mining lake - From acidity to natural neutralization

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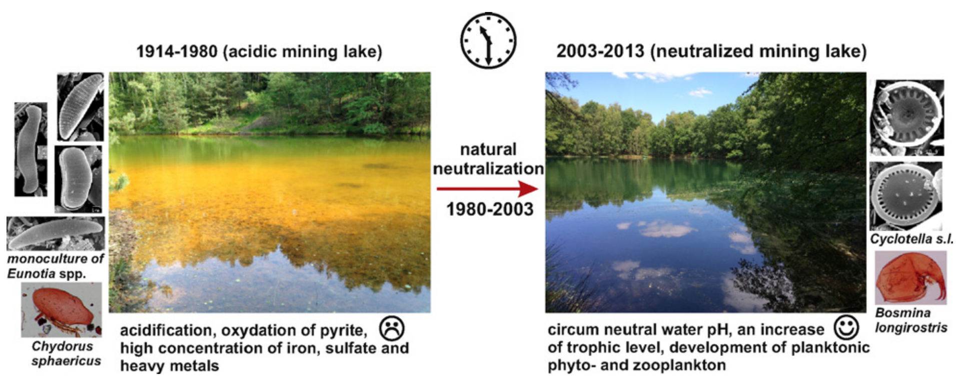
HIGHLIGHTS

- Originally acid water lake had poor phyto- and zooplankton populations.
- Process of natural neutralization lasted approximately 23 years.
- Presently, lake's ecosystem is similar to other shallow lakes in the region.
- Changes in the lake are representative for other mine lakes.

GRAPHICAL ABSTRACT



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ABSTRACT

Along the border of Poland and Germany (central Europe), many of the post-mining lakes have formed “an anthropogenic lake district”. This study presents the evolution of a mining lake ecosystem (TR-33) based on subfossil phyto- and zooplankton, isotopic data ($\delta^{13}C$, $\delta^{15}N$), elemental analyses of organic carbon and nitrogen (C/N ratio and TOC) and sedimentological analyses. Recently, lake TR-33 became completely neutralized from acidification and an increase in eutrophication began a few years ago. However, the lake has never been neutralized by humans; only natural processes have influenced the present water quality. From the beginning of the existence of the lake (1920s) to the present, we can distinguish four stages of lake development: 1) very shallow reservoir without typical lake sediments but with a sand layer containing fine lignite particles and very poor diatom and cladoceran communities; 2) very acidic, deeper water body with increasing frequencies of phyto- and zooplankton; 3) transitional period (rebuilding communities of diatoms and Cladocera), meaning a deep lake with benthic and planktonic fauna and flora with wide ecological tolerances; and 4) a shift to circumneutral conditions with an essential increase in planktonic taxa that prefer more fertile waters (eutrophication). In the case of lake TR-33, this process of natural neutralization lasted approximately 23 years.

1. Introduction

Many artificial lakes around the world were formed as a result of the end of lignite exploitation (e.g., Wollmann et al., 2000; Harrison et al., 2003; Moser and Weisse, 2011), and chemical processes in these lakes, such as the oxidation of pyrite (FeS_2) and other sulfide compounds, cause the release of sulfuric acids and, consequently, acidification. Mine lakes usually have very acidic or extremely acidic water, with pH levels ranging from 2 to 4 (Koschorreck and Tittel, 2002), and these water bodies are also characterized by high conductivity and high iron, sulfate and heavy metal concentrations (Moser and Weisse, 2011). Heavy metals that are released into aquatic environments impact

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primary producers; metal pollutants disrupt the protein structure and oxidative balance in algae, which primarily results from the metals binding to the sulfhydryl groups in the proteins (Tuovinen et al., 2012). An area where pyritic minerals are exposed to the atmosphere or where lignite beds come in contact with water or biological weathering (e.g., chemoautotrophic bacteria) is called acid mine drainage (AMD) (Luís et al., 2009). An important feature of AMD is that the sources of pollution can be active for years or even centuries after mine closure (Modis et al., 1998).

Along the border of Poland and Germany (central Europe), many of the post-mining lakes have formed "an anthropogenic lake district". The pH of these lakes varies between strongly acidic (pH ~2.5) to alkaline (pH ~9.0), and the lakes located in the Polish part of the region have never been neutralized by humans. However, natural neutralization processes that act over time are related to various chemical compounds that are washed out from sulfated lignite deposits or bonded to clays with good sorption capacity (Solski et al., 1988). For that reason, the lakes located in the study area have long pH gradients. In the past, lignite was extracted by underground and open pit methods. However, the mining industry has evolved since the second half of the 19th century, and the last mine (called "the Babina") in this region was closed in 1973. After the end of lignite exploitation, the excavation pits and/or collapsed sinks in the extraction galleries were flooded by rain and underground water. During the ontogenetic development of these lakes, the sulfate-iron-calcium type of water occurring in the acid pit lakes was transformed into water of an alkaline hydrogen-carbonate-calcium type. Due to different completion times of the lignite exploitation, the ages of the lakes vary between approximately forty-two and one hundred years, and studies have shown that younger lakes are more acidic than older ones (Solski et al., 1988). Due to the poor water quality, especially in the acidic pit lakes, the diversity of phyto- and zooplankton is very reduced, often limited to a few species, and the amount of biomass is generally low (Nixdorf et al., 1998; Moser and Weisse, 2011). An important factor influencing primary producers is the availability of nutrients and their consumption rates (Wollmann et al., 2000), but extremely low pH is the most limiting factor affecting the development and diversity of phyto- and zooplankton. However, in some of the older lakes, processes of natural neutralization are observed, which are mirrored in the recent pH of the water as well as in the modern phyto- and zooplankton populations.

The aim of our paper is to describe the individual development stages of the diatom and Cladocera communities in an anthropogenic lake (TR-33) from the beginning of its existence to the present. We also answer the following question: have phyto- and zooplankton communities changed from the end of lignite exploitation until the present? If so, we will try to estimate the length of time required to neutralize the particular lakes situated on the Łuk Mużakowa based on the results from the TR-33 sediment core. We chose this lake because it is located in the average lake zone of the anthropogenic lakeland; it is average in terms of its age, and the neutralization process is probably occurring. In our opinion, a lake of average age will be the most representative of the whole region in comparison to the "marginal" lakes, i.e., the youngest and oldest water bodies. We analysed diatom and cladoceran remains preserved in lake sediments collected in 2013, and additional investigations, such as isotopic data (δ^{13}C, δ^{15}N), elemental analyses of organic carbon and nitrogen (C/N and TOC) and sedimentological analyses, allowed for the determination of the rate and degree of change in the lake ecosystem. By dating the lake sediment core, this study can also be helpful in predicting the recovery of other lakes situated in this area that were formed at different times following exposure to mining.

The water bodies located in the study area have been analysed by many researchers, but the investigations have mainly concerned the chemistry of the lakes (Solski et al., 1988; Solski and Jędrczak, 1991a,b; Najbar and Jędrczak, 1998). A few biological analyses were performed by Najbar (1998) and Najbar and Jędrczak (1998), but these investigations mainly encompassed modern phyto- and zooplankton collected from littoral and pelagial lake zones and not their subfossil remains.

This is the first study of subfossil diatoms and Cladocera remains that combines isotopic and sedimentological analyses of dated lake sediments and encompasses the entire environmental history of a mine lake in Poland.

2. Materials and methods

2.1. Study area

The studied mining lake, TR-33 (N 51°36′50.4″; E 14°48′11.0″), is located on the Łuk Mużakowa (Fig. 1), which belongs to the Wzniesienia Łużyckie macroregion along the border of east Germany and west Poland. The lake parameters, such as pH, temperature, conductivity and the concentration of oxygen and selected elements, were measured in the surface water layers (Table 1). More than 100 anthropogenic lakes exist in the Łuk Mużakowa area, and their ages vary between 42 and approximately 100 years. The specific study lake originated from an open pit mine, where lignite exploitation ended in the 1920s. Iron compounds and acidic water changed the colour of the lakes from pastel greenish to reddish. The lakes are situated on the end of a moraine formed during the Riss glaciation that is in the shape of an arc that extends from the villages of Tuplice, Trzebiel and Łęknica in Poland to Weißwasser, Döbern, and Klein Kölzig in Germany. Miocene sediments, together with large lignite deposits, were underthrusted throughout a period of intense glacial activity, and the Łuk Mużakowa was formed by several glacial processes. Currently, this form is located ca. 30 m above the plane of the water-glacial sediments, and it is a unique glaciotectonic structure in Europe due to its shape, size and state of preservation. The Łuk Mużakowa Geopark (Muskauer Faltenbogen) was created in this area in 2001, and it was added to the UNESCO list. The study lake (TR-33) is situated close to Trzebiel, where the "Zur Hoffnung" lignite mine was active between 1854 and 1926 (Kupetz et al., 2004).

2.2. Core dating

Sediments from lake TR-33 were collected in September 2013 using a Kajak-type gravity corer. The sediment core was subsampled every 1 cm, and the samples were dried overnight at 105 °C. The chronology of the core was calculated based on the lead-210 dating method and validated with 137-caesium stratigraphy. The activity of lead-210, radium-226 and caesium-137 was measured directly with the Canberra low background, high-efficiency gamma spectrometer at the Laboratory for Isotope Dating and Environment Research at the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw. The activity of supported lead-210 was calculated by subtracting the radium-226 activity from the total lead-210 activity, assuming isotopic equilibrium. Then, a constant rate of supply (CRS) model for lead-210 dating was applied to calculate age (Appleby, 2001). An age-depth model for the entire sediment core was constructed with a MOD-AGE algorithm using a randomisation method for age estimation and a LOESS method for function fitting (Hercman and Pawlak, 2012; Hercman et al., 2014).

2.3. Organic matter analyses

Stable isotope data (δ^{13}C, δ^{15}N), total organic carbon (TOC) and the C/N ratios were used to determine the historical changes in the accumulation of organic matter in the studied pit lake. Samples were pretreated with 10% HCl to remove carbonates. These analyses were performed at the Stable Isotope Laboratory of the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw using a Thermo Flash EA 1112 HT elemental analyser connected to a Thermo Delta V Advantage isotope ratio mass spectrometer in a continuous flow system. The carbon isotopic composition and TOC were the tools used to