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Experimental eutrophication of a shallow acidic mining lake and effects on the phytoplankton

Dieter Lessmann, Andrew Fyson & Brigitte Nixdorf
Chair of Water Conservation, Brandenburg University of Technology, P.O. Box 101344, 03013 Cottbus, Germany
E-mail: lessmann@tu-cottbus.de

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Abstract

Acidic mining lakes offer an opportunity to investigate ecological development under extreme geochemical conditions. Low pH combined with high ionic and metal concentrations allows only a small number of species, in particular nanoflagellates, to occur. In these lakes, important nutrients such as phosphorus and inorganic carbon are scarce and limit primary production. In order to investigate the neutralization potential of sulphate reducing processes and controlled eutrophication, in Lake Koyne 113 (Brandenburg, Germany), a new technique for the remediation of acidic waters was tested by adding organic material to the lake in jute bags ("Biobags"), which should form anoxic microbial reaction compartments and increase primary production by adding nutrients to the water. This treatment was expected to have profound effects on the lake ecosystem. The hydrochemical and biological effects were observed within an accompanying monitoring programme. The experiment led to an increase in the organic carbon and total phosphorus concentrations. The influence on other physical and chemical variables was not obvious. Phytoplankton species composition remained unchanged and was still determined by the high acidity. Algal biomass rapidly increased after nutrient addition and chlorophytes replaced chrysophytes as the dominant phytoplankton group.

Introduction

Since the mid 1990s, mining lakes have been of growing interest for limnological research. They offer a remarkable opportunity for limnologists to investigate ecological development under harsh geochemical conditions. Because of their often extreme acidification, resulting from pyrite oxidation combined with high ionic and metal concentrations, they are hydrochemically a distinct lake type (Geller et al., 1998). Acidification controls the biocoenoses in different ways. High hydrogen ion and aluminium concentrations allow only a small number of species with special adaptations to survive in these extreme habitats (Lessmann et al., 2000). Important nutrients occur only in low concentrations. Phosphorus is removed from biological circulation through co-precipitation with iron hydroxides. In addition, a continuous decrease in inorganic carbon occurs in deeper lakes in the epilimnion during stratification (Nixdorf et al., 1998a, b; Lessmann & Nixdorf, 2000). Therefore, nearly all Lusatian mining lakes are oligotrophic or occasionally mesotrophic, in spite of the fact that inflowing groundwater phosphorus concentrations can be high. In addition, in lakes flooded with river water rich in nutrients, no apparent increase in the trophic status occurred (Lessmann et al., 2003). This is in contrast to the trophic status of most shallow natural lakes of the ecoregion which are more or less strongly eutrophicated and characterized by permanent massive phytoplankton blooms (Mathes et al., 2003).

A number of lake treatments will be or have been employed to overcome acidification by neutralization using technical measures such as liming and flooding with alkaline river water, or ecotechnological measures using lake internal biological processes to increase primary production and sulphate reduction (Davison et al., 1989; Wendt-Potthoff & Neu, 1998; Fyson et al., 1998a, b). Such a new ecotechnological remediation technique was used in Lake Koyne 113, a small, shallow, extremely acidic mining lake. The treatment was expected to have profound effects on the lake ecosystem. Results of the accompanying monitoring programme are described with special regard to the effects on the hydrochemical conditions and the distinct phytoplankton assemblage of this type of lake.

The experimental Mining Lake Koyne 113

Mining Lake Koyne 113 is located near Lauchhammer in the Lusatian mining district in the German state of Brandenburg. It was infilled with groundwater following mine closure of an open-cast lignite mine in 1954. With an area of 100 000 m^2 and a volume of 100 000 m^3, Koyne 113 is one of the smaller mining lakes of the region. This lake currently has a mean depth of 1.0 m and a maximum depth of 2.5 m.

Materials and methods

A new technique for the remediation of acidic mining lakes has been tested in Lake Koyne 113 since 1999. By this method, sulphur, metal and hydrogen concentrations should be reduced by reversing the pyrite oxidation process under anoxic conditions in so-called "Biobags" and by increasing primary production through the addition of nutrients to the lake. The scientific background of such ecotechnological treatments is described by Nixdorf & Uhlmann (2002) and Uhlmann & Nixdorf (2002). The Biobags are jute bags (circa 50 × 60 cm) filled with cut-up beer and water bottle labels which were an organic waste, enriched with alkaline detergents from the bottle cleaning and usually serve as a compost basis. Analyses of the Biobag material showed that it mainly consisted of organic carbon, organically bound nitrogen and also some phosphorus (Table 1). Concentrations of heavy metals were low enough to fulfil the demands for the declaration as environment friendly quality compost. The bags have been placed in the pelagial of the lake, fastened to buoys on four occasions: In November 1999 (adding 59 t to the lake), March 2000 (86 t), October 2000 (47 t) and March 2001 (51 t). In total, 243 t of the Biobag material has been added to the lake.

Table 1. Main components of the Biobag material (Data: Umweltschutz Nord GmbH)

Substance	Unit	Concentration
Total Carbon (mainly C_{org})	mg kg^{-1} dw	486 000
Total Nitrogen	mg kg^{-1} dw	6362
Ammonium-N	mg kg^{-1} dw	6.48
Nitrate-N	mg kg^{-1} dw	121
Phosphate-P	mg kg^{-1} dw	94

The effects of the lake treatment were investigated within a monitoring programme between June 1998 and April 2002 with a usual sampling frequency of 4–8 weeks apart from the frequency of phytoplankton sampling which especially had a break in 1999. The programme included depth profiles of water temperature, oxygen concentrations, pH and conductivity with a multi-parameter probe (HYDROLAB H20). Samples for chemical and biological analyses were taken as mixed samples at 0.5 m depth intervals from surface to bottom. The concentrations of the major cations, anions and trace elements were determined by ion chromatography (Dionex DX 100) and atomic absorption spectroscopy (Perkin-Elmer AAS 3100), respectively (DEV, 1986–1998). Total organic carbon (TOC), dissolved organic carbon (DOC) and total inorganic carbon (TIC) concentrations were measured by infra-red spectrometry (DIMATEC Dima-TOC 100); ammonium, phosphate and chlorophyll-*a* concentrations spectrophotometrically (Perkin-Elmer Lambda) by standard German methods (DEV, 1986–1998). The acidity was determined by titration with sodium hydroxide up to pH 4.3 (base capacity $K_{B4.3}$) and up to pH 8.2 (base capacity $K_{B8.2}$) (DEV, 1986–1998). The phytoplankton samples were fixed in Lugol's solution and determined and counted by using the Utermöhl technique (Utermöhl, 1958). The biovolumes were calculated from measurements of the cell sizes.

Results and discussion

Abiotic effects

During the experimental treatment, the water level increased from 96.2 m a.s.l. in 1998 to 96.7 m a.s.l. in 2001 connected with the re-increase of the groundwater table following cessation of mining activities. During the summer, usually from May to September, a decrease of a few decimetres in depth occurred due to the high evaporation at that time. The lake was well mixed nearly the whole year despite short stratification periods in summer lasting just a few days. These short stratifications were accompanied by a decrease in oxygen concentrations in the lower part of the water column which might have been due not only to decomposition processes but also to chemical oxidation of the iron of the inflowing groundwater as known from other mining lakes (LUA Brandenburg, 2001). In total, a slight increase in the oxygen saturation was observed during the lake treatment (Table 2), likely an effect of the increased phytoplankton activity.

The high electrical conductivity of Lake Koyne 113 was not clearly influenced by the Biobag addition to the lake (Table 2). The fluctuations corresponded to changes in water depth with lower values in winter and spring, and higher values in summer and autumn during lower water levels.

Up to now, no overall increase in pH has occurred which was the main objective of the Biobag treatment. The high acidity of the inflowing groundwater from the overburden dumps likely prevented any measurable alkalinization effect. With minor changes, the pH maintained around 2.5 (Table 2). Changes in the parameters acidity ($K_{B4.3}$ and $K_{B8.2}$), magnesium, calcium, sulphate, iron, aluminium and manganese over time are also given in Table 2 and show no obvious relationship to the applied treatment.

With every Biobag addition to the lake, the organic carbon concentrations increased (Table 2). After the fourth campaign, TOC and DOC concentrations were more than twice as high as prior to the start of the experiment.

The concentrations of the inorganic carbon are of special importance for the primary production because the measured concentrations of sometimes less than 0.2 mg l^{-1} suggest a limitation for primary producers during some times of the year (Fig. 1). Fluctuations were considerable, and prior to the third campaign, the addition of the Biobag material seemed to have no effect on the TIC concentrations which continuously stayed low. Since the winter 2000/2001, periods with increased TIC concentration occurred irregularly.

The characteristics of the inorganic carbon budget of acidic waters have to be considered as a limitation for production processes. Under low pH conditions, inorganic carbon is essentially only present as CO_2 and the exchange with the atmosphere does not allow higher surface concentrations than atmospheric equilibria (Stumm & Morgan, 1996). Nevertheless, higher carbon dioxide concentrations can occur because of the permanent inflow of CO_2-rich groundwater and also from respiration and decomposition of organic

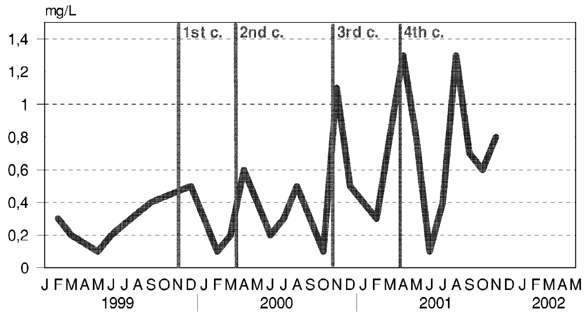

Figure 1. Dynamic of the inorganic carbon concentrations in Lake Koyne 113. The four additions of Biobags are indicated by bars.

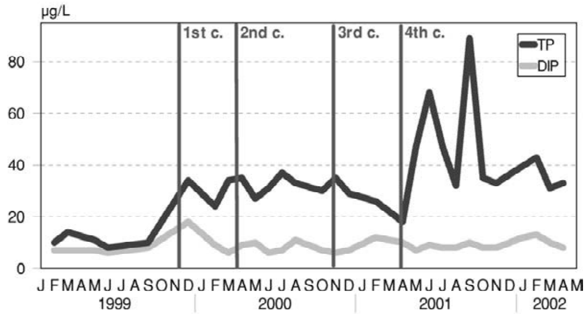

Figure 2. Development of the phosphorus concentrations in Lake Koyne 113. The four additions of Biobags are indicated by bars.

matter at the sediment surface (Nixdorf et al., 1998a, b; Lessmann & Nixdorf, 2000). Therefore, the inorganic carbon concentrations of the lake are determined mainly by the intensity of the mixing process of the water column and the demand of the phytoplankton. Both factors lead to larger fluctuations of the TIC concentrations in shallow lakes than in deep lakes.

There was a decrease in nitrogen concentrations through the study period, especially for the ammonium concentrations and may partly be related to the increased nitrogen demand of the phytoplankton (Table 2). There is no nitrification under the acidic conditions of Lake Koyne 113 (Ender et al., 2001).

In general, the low pH and high concentrations of Fe and Al reduce the concentration of dissolved inorganic phosphorus (DIP) to the level of detection (Fig. 2). This was due to chemical adsorption (mainly non-stoichiometric iron and aluminium phosphorus compounds) in the sediment and due to the co-precipitation with the metal oxyhydroxides. As a result, algal growth can be P-limited in pelagic waters (Krumbeck et al., 1998).

In Lake Koyne 113, total phosphorus (TP) concentrations increased considerably following the first and fourth Biobag additions (Fig. 2). Dissolved inorganic

Table 2. Median physical and hydrochemical data of Lake Koyne 113 from June 1998 to April 2002 prior the treatments and after the first to fourth additions of Biobags (*n*: number of samples)

Variable	Unit	Prior treatm.	1st c.	2nd c.	3rd c.	4th c.
n	–	10	3	6	4	12
Oxygen sat.	%	93	94	93	98	101
Conductivity	μS cm^{-1}	3120	3140	3160	3300	3230
pH	–	2.5	2.6	2.5	2.6	2.5
$K_{B4.3}$	mmol l^{-1}	10.8	9.9	10.8	10.2	10.1
$K_{B8.2}$	mmol l^{-1}	13.8	13.2	13.8	14.0	14.9
TOC	mg l^{-1}	2.9	5.4	6.2	7.6	8.0
DOC	mg l^{-1}	2.7	3.9	4.2	6.0	6.4
Mg	mg l^{-1}	30.1	29.3	31.3	31.5	30.8
Ca	mg l^{-1}	270	260	260	320	340
Cl	mg l^{-1}	55.6	59.6	61.0	68.6	69.3
NH_4	mg l^{-1}	15.1	14.2	13.2	11.5	10.5
NO_3	mg l^{-1}	1.2	1.2	0.9	0.5	0.7
SO_4	mg l^{-1}	1590	2060	2180	1880	2860
TFe	mg l^{-1}	115	120	115	125	135
Al	mg l^{-1}	37	33	36	42	44
Mn	mg l^{-1}	3.2	2.2	2.0	3.0	3.4

phosphorus concentrations showed only small changes during the whole investigation period (Fig. 2). Thus phytoplankton seemed to be able to effectively use the increased phosphorus supply.

Effects on the phytoplankton

Following Biobags addition, the phytoplankton species composition did not change from the pre-experiment assemblage. With only five morphologically distinguishable taxa, the number of species always remained very low. The most abundant taxa were *Ochromonas* spp., *Chlamydomonas* spp. and an as yet unidentified, very small coccal green alga (described as *Chlorella*-like). Similar, very small forms have been found in other acidic mining lakes in the area (Fyson & Rücker, 1998). In addition, *Eunotia exigua* and *Lepocinclis teres* occurred sporadically in Lake Koyne 113.

Both *Ochromonas* spp. and *Chlamydomonas* spp. are nanoflagellates which are able to migrate in the water column and reproduce rapidly. They are the most abundant taxa in most of the documented extremely acidic Lusatian mining lakes (Lessmann et al., 2000). *Chlamydomonas* is morphologically diverse and several species are likely to be present in the Lusatian lakes (Lessmann et al., 2000). *Ochromonas* spp. from acid lakes are often observed to contain bacterial cells and are therefore assumed to be mixotrophic or phagotrophic (Sanders & Porter, 1988; Rothhaupt, 1997). Diatoms regularly occur in plankton samples from the Lusatian acid lakes, but rarely dominate. Among them, *Eunotia exigua* is the most acid-tolerant diatom species known, classified as acidobiontic (Ettl et al., 1978–1999), and has often been found in mining lakes with a pH between 2 and 3 and with high concentrations of heavy metals (Lessmann et al., 2000).

The reaction of the phytoplankton biomass to the Biobag additions was rapid and chlorophyll-*a* maximum concentrations increased from campaign to campaign with maxima from 28 μg l^{-1} to 85 μg l^{-1} (Fig. 3). Maxima were found in spring, especially in March and also between July and September. TP concentrations were well related to these algal maxima (Figs 2 and 3). The Pearson correlation coefficient showed a medium significant correlation of $r = 0.50$ between chlorophyll-*a* and TP concentrations.

However, algal growth depends also on the availability of inorganic carbon. Sometimes, a limitation of primary production by inorganic carbon in most of the extremely acidic lakes is likely (Schindler &

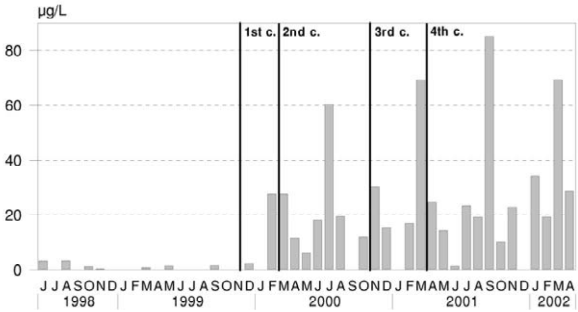

Figure 3. Changes in the chlorophyll-*a* concentrations in Lake Koyne 113. The four additions of Biobags are indicated by bars.

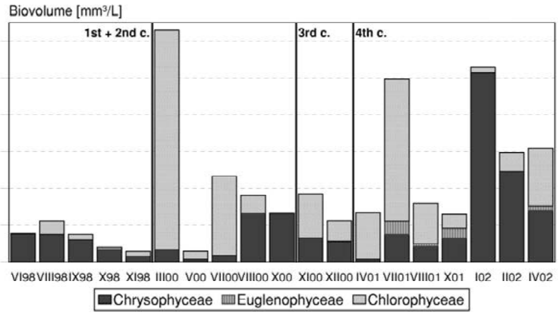

Figure 4. Development of the dominance structure of the phytoplankton biocoenoses in Lake Koyne 113 on the basis of biovolume classes. The four additions of Biobags are indicated by bars.

Holmgren, 1971; Goldman et al., 1974; Kapfer et al., 1999; Krumbeck et al., 1998). This is well documented for stratified acidic lakes in the epilimnion during summer stagnation and plays a major role in the seasonal succession of the phytoplankton (Lessmann & Nixdorf, 2002). In Lake Koyne 113 an inorganic carbon limitation might be obvious, for example in June 2001 when TIC concentrations were less than 0.2 mg l^{-1} (Figs 1 and 3). On the other hand and as aforementioned, some of the occurring taxa can be mixotrophic and may also live on dissolved organic carbon and bacteria. The specific conditions of shallow acidic mining lakes seem to favour the growth of large bacterial cells with high specific activity. In Lake Koyne 113 the bacterial activity is as high as in hypertrophic hardwater lakes (Nixdorf & Jander, 2003).

Prior to the start of the treatment, the phytoplankton was dominated by Chrysophyceae (*Ochromonas* spp.) but with relatively low biovolume (Fig. 4). *Chlamydomonas* spp. and the *Chlorella*-like species were also present. In 2000 and 2001, these two taxa became dominant, particularly *Chlamydomonas* spp.. In winter 2001/2002, *Ochromonas* was the dominant genus again. However, it should be noticed that the phytoplankton sampling frequency was too low to reflect the actual seasonal succession of the nanoflagellates with their fast reproduction cycles.

Nevertheless, the experiment showed that biodiversity in the lake also after the eutrophication was determined by the acidity, whereas algal biomass was more clearly related to the trophic state and could rapidly be increased by nutrient addition. As in natural lakes phosphorus played a major role but was not the only reason for the observed changes. The increase of the biomass could be assumed to be a combined effect of the increase in TP and DOC concentrations and the supply with inorganic carbon (also see: Lessmann & Nixdorf, 2002; Beulker et al., 2003).

Conclusions

The experimental addition of organic nutrient rich material to the acidic mining lake Koyne 113 led to an increase in the organic carbon and total phosphorus concentrations. The inorganic carbon concentrations also increased but showed greater fluctuations assumed to depend primarily on the mixing intensity of the water body and the requirements of the phytoplankton. An influence on other chemical variables was not obvious. In particular, the severe acidification could not be reduced. Therefore the new technique failed its principal objective.

The phytoplankton species composition remained unchanged and was also after eutrophication determined by the high acidity, but Chlorophyceae instead of Chrysophyceae maintained the phytoplankton after the first treatment. The algal biomass could rapidly be increased by the nutrient addition but great fluctuations occurred with algal-blooms in spring and summer. A diverse network of the availability of different nutrients (in particular phosphorus and as in deep lakes also inorganic carbon) and the physiological adaptation potential of the algae can be assumed to be responsible for the reactions of the phytoplankton coenosis.

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