Limnologica 40 (2010) 148–155

Contents lists available at ScienceDirect

Limnologica

journal homepage: www.elsevier.de/limno

Pit lakes of the Central German lignite mining district: Creation, morphometry and water quality aspects

Martin Schultze[a,*], Karl-Heinz Pokrandt[b], Wolfram Hille[b]

[a] UFZ Helmholtz Centre for Environmental Research, Department of Lake Research, Brückstraße 3a, D-39114 Magdeburg, Germany
[b] Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft, Leipzig, Germany

ARTICLE INFO

Article history:
Received 9 September 2009
Accepted 13 November 2009

Dedicated to Prof. Dr. Walter Geller on the occasion of his 65th birthday anniversary

Keywords:
Pit lake
Lignite mining
Acidification
Remediation
Eutrophication
Trace contaminants
Saline groundwater
Water management

ABSTRACT

About 140 pit lakes exist in Central Germany. These have resulted from lignite mining and are important parts of the post-mining landscape in the Central German lignite mining district. Their water quality is mainly influenced by the consequences of pyrite oxidation, i.e., acidification or results of natural or artificial neutralization. The major way of filling as well as a cheap and successful measure against acidification was the diversion of river water into the lakes or their filling with neutral water from mines still operating. Eutrophication, contamination by industrial pollutants and infection with pathogens imported with river water were found to be unimportant threats for the pit lakes in the Central German lignite mining district. Intrusion of naturally saline groundwater from deeper underground resulted in some cases in elevated concentrations of sodium chloride and in meromixis. The diverse uses of the lakes (e.g. recreation, nature conservation, water management) indicate that the pit lakes fulfil widely the typical functions of lakes in a landscape. The creation, the current state of water quality and lessons learned in water quality management are reported upon for the pit lakes of the Central German lignite mining district.

Introduction

Lakes and rivers are dominant inland surface waters and important parts of the landscape. Because of their properties, lakes have particular ecological and socio-economic functions as habitat for aquatic organisms, sites for fishery and recreation, etc. Artificial lakes and reservoirs should fulfil those functions as far as possible.

The region called "Central Germany", i.e., the area described by circles around Leipzig and Halle/Saale of about 150 km in diameter, is poor in natural lakes. Surface mining has changed this situation, mainly within the last 120 years. Many artificial lakes formed in former excavations of clay, sand and gravel, in former quarries and in former open-cast lignite mines when the respective operations ceased. This paper deals only with lakes in former open-cast lignite mines. For simplification, these lakes are generally called pit lakes in this paper.

There are about 140 pit lakes in the Central German lignite mining district today, i.e., about 28% of the pit lakes in all German lignite mining districts. Fig. 1 shows a map of the mining district including the lakes which are planned to form in the currently operating lignite mines.

When managing pit lakes, one may be faced with one or more of the following concerns with respect to water quality (Klapper and Schultze, 1995):

- Acidification caused by pyrite oxidation and the accompanying mobilization of acidity, iron and sulphate.
- Eutrophication caused by excessive import of phosphorus and nitrogen via river water for filling or flushing the lake or inappropriate lake use (e.g. excessive feeding in aquaculture).
- Contamination with industrial pollutants caused by groundwater inflow from industrial sites or waste deposits in the vicinity of pit lakes.
- Salinization by highly saline ground water.
- Infection by import of pathogens via river water which in turn was impacted by waste water.

In this paper, we report on the creation and the current characteristics of the lakes in the former lignite open-cast mines of the Central German lignite mining district. In addition to the description of the current conditions, lessons learned are presented.

Data sources

The data presented below originate from lake monitoring in spring 2007, as far as possible. Morphometric data were taken

* Corresponding author. Tel.: +49 391 8109400; fax: +49 391 8109150.
E-mail address: martin.schultze@ufz.de (M. Schultze).

0075-9511/$ - see front matter © 2009 Elsevier GmbH. All rights reserved.
doi:10.1016/j.limno.2009.11.006

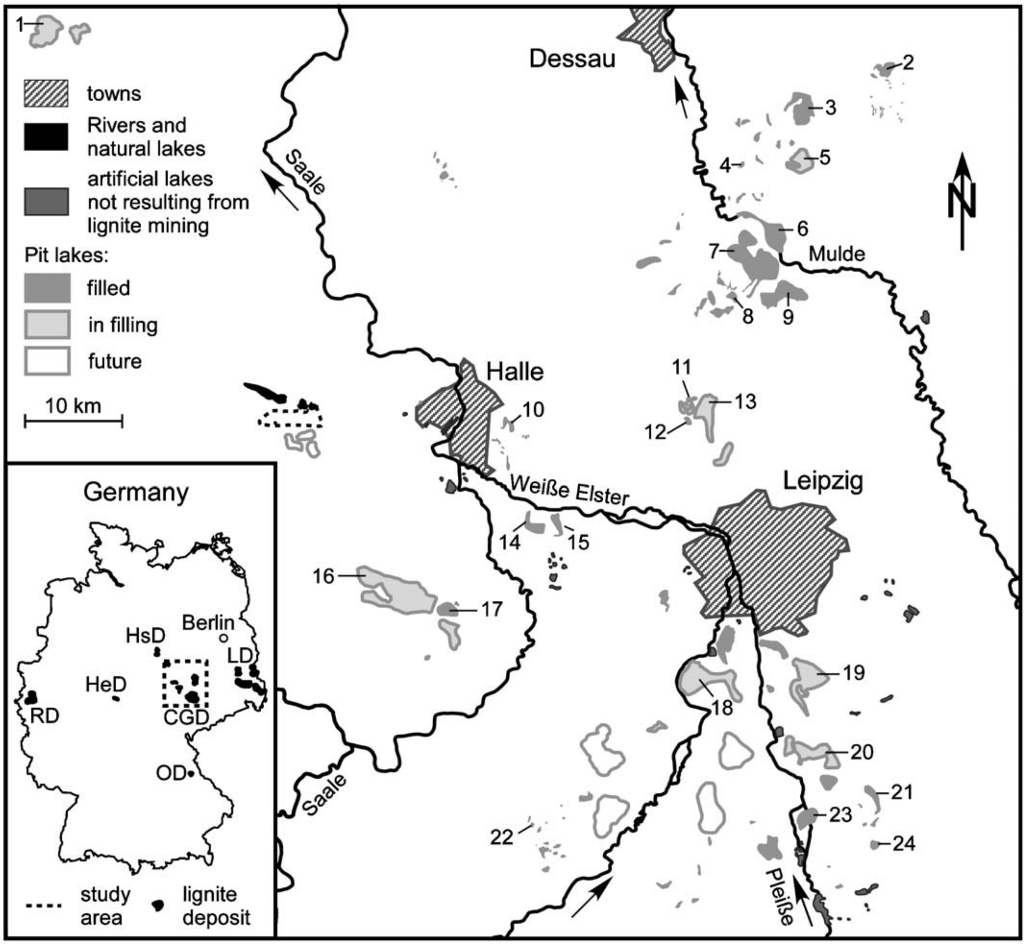

Fig. 1. Map of the Central Germany mining district showing the pit lakes resulting from lignite mining, the major rivers and some towns for orientation. The lakes mentioned in the text are: 1 – Lake Concordia, 2 – Lake Bergwitz, 3 – Lake Gremmin, 4 – Lake Golpa IV, 5 – Lake Gröbern, 6 – Muldereservoir, 7 – Lake Goitsche, 8 – Lake Paupitzsch, 9 – Lake Seelhausen, 10 – Lake Hufeisen, 11 – Lake Grabschütz, 12 – Lake Zwochau, 13 – Lake Werbelin, 14 – Lake Wallendorf, 15 – Lake Rassnitz, 16 – Lake Geiseltal, 17 – Lake Runstedt, 18 – Lake Zwenkau, 19 – Lake Störmtal, 20 – Lake Hain-Haubitz, 21 – Lake Bockwitz, 22 – Lake Vollert Süd, 23 – Lake Borna, 24 – Lake Harthsee. The dotted black line west of Halle indicates the natural Lake Salziger See, which disappeared in 1890 due to dewatering operations of underground mining for copper. Dewatering of the lake basin is still performed although copper mining ceased and the underground galleries are flooded. The lake will be re-established in the future. Lignite mining districts in Germany: RD – Rhineland district, HeD – district of Hessen, HsD – district of Helmstedt, OD – district of Oberpfalz, CDG – Central German district, LD – Lusatian district.

from the web sites of Mitteldeutscher Seenkatalog (community of governmental and non-governmental institutions concerned with and interested in the sustainable development of lakes in Central Germany; www.mitteldeutscheseen.de) and of Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft (LMBV; state company responsible for the remediation of the former lignite mines in eastern Germany; www.lmbv.de). Water quality data were provided by the LMBV as far as the LMBV was responsible for water quality monitoring in 2007. The Landestalsperrenverwaltung des Freistaates Sachsen (authority of the federal state of Saxony responsible for the management of reservoirs and lakes in Saxony) provided data for pit lakes according to its responsibility. Data of other lakes were taken from web-published results of lake monitoring in the federal state of Saxonia-Anhalt in 2007 (www.sachsen-anhalt.de/LPSA/index.php?id=27953) or for some cases from a report on the status of German pit lakes by Nixdorf et al. (2001). The data from Nixdorf et al. (2001) can still be considered as representative since the respective pit lakes are older and show mainly seasonal variations in water quality but nearly no inter-annual trends. Less data were available from small and/or old lakes. Therefore, the small and/or old pit lakes are generally underrepresented in this study.

Creation

In the 19th century or in some cases even earlier, lignite mining began where lignite seams reached the surface. The exploitation was performed by hand with very simple technical devices. Accordingly, the first surface mines were very small. The same applies for the first pit lakes forming in such abandoned mines at the end of the 19th or at the beginning of the 20th century, e.g. the Gniester lakes south of Lake Bergwitz. The surface areas of these lakes are in the range of some 100 m^2 only and the depths are in the range of 10 m or less. The pressure of Pleistocene glaciation resulted in folding of Tertiary layers including lignite seams in the region of the Gniester lakes. The tops of the lignite folds reached the surface (Litt and Wansa, 2008). Larger excavators and improved dewatering technology resulted in larger mines and, consequently, larger pit lakes. However, relatively small lakes may form due to technical reasons and efficient overburden handling even today, e.g. Lake Zwochau and Lake Grabschütz.

Until the 1970s, the filling of the lakes was exclusively based on local runoff and rebound of the groundwater level in the Central German lignite mining district after ceasing dewatering operations. The so-called Muldereservoir with a maximal depth of 26 m and a total volume of 118×10^6 m^3 was the first lake in the Central German lignite mining district, which was filled with river water in 1975 and 1976. For that process, a new artificial river bed was constructed on a 10 km long trench including two residual voids of the former mine Muldenberg (the latter forming the Muldereservoir today). The River Mulde still flows completely through this lake (Junge and Jendryschik, 2003). Due to this redirection of the River Mulde, mining became possible in the former floodplain. It resulted in the subbasins Muehlbeck and Doebern of Lake Goitsche and the so-called Pouch peninsula between them, which consists of an overburden dump inside the former mine (Trettin et al., 2007).

As a consequence of German re-unification, many open-cast lignite mines were closed at the beginning of the 1990s. Therefore, many pit lakes were created in the last nearly 20 years or are currently in filling (Krüger et al., 2002). For fast filling of the pit lakes, river water or water from mines still operating (Jolas, 1998) was used as far as possible. The initial reason for fast pit lake filling was the stabilization of the side walls of the mining voids which became the slopes of the lake basins. If the filling happens faster, they can remain steeper than in the case of slow filling, particularly if the water level in the rising lakes can be kept higher than the groundwater level in the surrounding aquifers until the final water level of the lakes is reached. The limitation or even prevention of lake acidification due to pyrite oxidation in the mined material became a second reason for fast filling (Klapper and Schultze, 1995; Jolas, 1998; Zschiedrich et al., 2007). This aspect will be discussed in more detail in the "Water chemistry" section.

The diversion of river water has been used for pit lake filling as follows: River Saale for Lake Runstaedt and Lake Geiseltal, River Weiße Elster for Lake Wallendorf, Lake Rassnitz and Lake Werbelin, River Mulde for the Muldereservoir, Lake Goitsche, Lake Seelhausen, Lake Gremmin and Lake Gröbern and River Selke for Lake Concordia. The diverted amount of water has been limited due to requirements of other already established water use (e.g. extraction of water for industrial purposes) and of ensuring the ecological functioning of the rivers. The overall amount of diverted river water was 792×10^6 m^3, accounting for 56.6% of the filling of the lakes in the period 1993–2007. In the same period, 433×10^6 m^3 of water from dewatering of mines still operating was used for pit lake filling, accounting for 30.9% of the lake filling. Groundwater contributed 12.5%, i.e., 175×10^6 m^3 (LMBV, 2008). The filling of the Muldereservoir is not included in the data above because it happened earlier. The flood water which passed into Lake Goitsche in August 2002 (Klemm et al., 2005) also had to be excluded due to the lack of possibilities for measuring its amount.

Morphometry and stratification

Fig. 2 gives an overview of the volumes, surface areas and maximal depths of the pit lakes in the Central German lignite mining district. The largest lake is Lake Geiseltal which is still in filling (75% of lake volume was filled as of December 31, 2008). Its final volume will be 423×10^6 m^3, its final surface area will be 18.5 km^2 and its maximal depth will be 80 m. In Fig. 2, Lake Geiseltal is included with its final morphometric data like all other lakes, which are still in filling or which are planned to be filled in the next few decades when the currently operating mines will be mined out.

The morphometry of the pit lakes is the combined result of geological conditions of the lignite deposits, the excavation technology, the filling rate and some local aspects such as planned use of the lake insofar as known and considered during mining. Eissmann (2002a, b) gives an overview of the geological conditions in the Central German lignite mining district. Fig. 3 shows a simplified schematic depiction of the typical arrangement of pit lakes, overburden dumps and untouched underground. The lignite is of Tertiary age and is imbedded and overlain by layers of clay, sand and gravel from the Tertiary and the Quaternary. Consequently, the steepness of the slopes of the mining voids and the lakes is limited because all these materials are unconsolidated rock. This is an important difference to pit lakes in hard rock environments, which are common in many other coal mining regions of the world and which usually occur at metal mining sites (e.g. Doyle and Runnells, 1997; Shevenell et al., 1999; Sanchez Espana et al., 2008).

An important aspect of the geology of the Central German lignite mining district is the occurrence of Permian and Triassic salt deposits (mainly sodium chloride and calcium sulphate) in the deeper underground, often more than 100 m below the lignite seams. In some cases, the widespread subrosion of these salt deposits formed wide depressions which were filled with lignite

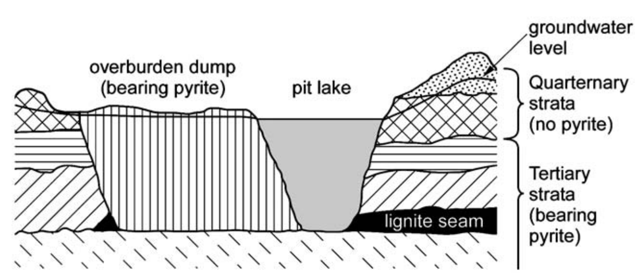

Fig. 3. Schematic cross-section of a former open-cast lignite mine showing the spatial relation of pit lake, overburden dump and untouched underground, the typical relation of groundwater and lake level after groundwater rebound, and the location of pyrite.

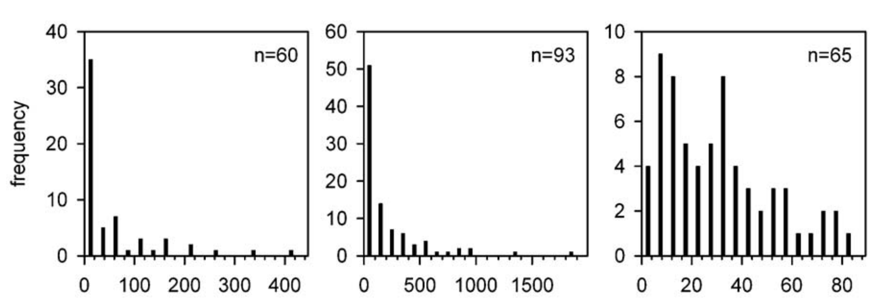

Fig. 2. Frequency distribution of the morphometric data of the pit lakes in the Central German lignite mining district (as far as data are available from the sources mentioned above). All data represent the final water level of the pit lakes. The current data are smaller for lakes which are still in filling.

over a long period syn-genetically. In other cases, local depressions formed syn- or post-genetically resulting eventually in local depressions of the pit lake bottom if the lignite in these local depressions was excavated and the depressions were not filled with overburden. For more details see Eissmann (2002a, b).

Usually the pit lakes are dimictic or monomictic, depending on the occurrence of an ice cover in winter. However, meromictic lakes also developed. In some cases, the intrusion of saline water from the above-mentioned salt deposits is the reason for meromixis: Lake Hufeisensee, Lake Rassnitz and Lake Wallendorf (Stottmeister et al., 1999; Heidenreich et al., 1999; Trettin et al., 2006). In other cases, inflowing groundwater with high concentrations of dissolved solids due to pyrite oxidation and its consequences caused the formation and persistence of monimolimnia. Examples are Lake Goitsche (Boehrer et al., 2003) and Lake Störmtal. In Lake Vollert Süd, meromixis resulted from the filling of the lake with waste waters of coke production containing very high concentrations of organic contaminants (260–690 mg/L DOC, mainly consisting of poly-aromatic, humic-like substances and phenolic compounds; Stottmeister et al., 1998) and from sheltering the lake from wind impact by surrounding side walls and forest. The applied remediation technology (a sequence of flocculation with iron, neutralization and fertilization) stabilised the meromixis via accumulation of the organic contaminants in the monimolimnion and the sediment (Stottmeister, 2008).

Water chemistry

As already mentioned above, acidification due to pyrite (FeS_2) oxidation is the major problem of water quality in pit lakes. Pyrite occurs in the Tertiary strata and, consequently, also in the overburden dumps (Fig. 3) and is the result of microbial reduction of iron and sulphur during and after the formation of the lignite. Pyrite is stable as long it remains under anoxic conditions. The dewatering of the underground and the excavation of the overburden and the lignite cause aeration of the pyrite and thus its microbial oxidation during and after mining. The grain size of the pyrite particles is usually in the range of millimetres. The following equations describe the pyrite oxidation and the production of acidity (only simplified net-reactions; for more details see e.g. Evangelou, 1995)

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (1)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (2)$$

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \quad (3)$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad (4)$$

After start of the oxidation process via reaction (1), usually reaction (2) becomes the dominating pathway of pyrite oxidation (Evangelou, 1995). At least a part of the acidity produced by pyrite oxidation is already neutralized underground along its transport by trickling water and groundwater before the water enters the pit lake. The following reactions and processes are the most important ones consuming acidity along the path from pyrite oxidation sites to pit lakes (only simplified net-reactions; for more details see e.g. Stumm and Morgan, 1996)

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \quad (5)$$

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2O + CO_2 \quad (6)$$

$$XM + nH^+ \rightarrow XH + M^{n+} \quad (7)$$

$$KAlSi_3O_8 + 7H_2O + H^+ \rightarrow Al(OH)_3 + 3HSiO_4 + K^+ \quad (8)$$

Reaction (5) happens in the groundwater and in the aqueous phase of the soil (buffering of acidity by bicarbonate) whereas Eqs. (6)–(8) describe buffering reactions between the underground solids and the acid trickling water or groundwater: buffering by carbonates (6), by ion exchange ((7), whereby X is e.g. a clay mineral and M is a metal) or by silicates (8). However, since iron is mainly transported as ferrous iron by the groundwater, reactions (3) and (4) cause a drop in pH of groundwater entering the pit lake due to the availability of oxygen in the pit lakes.

Initially, about 50% of the pit lakes in the Central German lignite mining district were acid or had the potential to turn acidic without special measures. The other about 50% of the pit lakes never had acid water due to local geological conditions (relatively low pyrite content combined with relatively high content of carbonates in the overburden). Fig. 4 shows that today a much higher percentage of the lakes are neutral. This is mainly the result of filling with river water and well-buffered water from dewatering of operating mines. Lake Bockwitz was neutralized by addition of soda ash (Na_2CO_3; Neumann et al., 2008; Rönicke et al., this issue) whereas Lake Hain-Haubitz was neutralized by a combination of filling with water from operating mines and addition of lime. A number of initially acid pit lakes became neutral without special remediation measures. Experiences from these pit lakes showed that the neutralizations without special measures may require periods varying from a few years to some decades. Examples are Lake Nenkersdorf, which became neutral within 5 years, and Lake Bergwitz, where neutralization required about 25 years after its filling by groundwater and local runoff (Jordan and Weder, 1995). The mechanisms of neutralization in such cases are (i) natural washout and flushing of the lakes and of the underground where the acidifying substances originate from, (ii) the neutralization by inflow of bicarbonate with naturally neutral groundwater and (iii) microbial sulphate reduction. The natural occurrence of sulphate reduction was reported for German pit lakes e.g. by Peine and Peiffer (1998) and for ground water in overburden dumps by Hoth et al. (2005). However, the observed net rates of sulphate reduction are small and, therefore, the contribution to neutralization is limited.

Although the majority of pit lakes are neutral today (Fig. 4) and the remaining acid lakes in the Central German lignite mining district are expected to be neutralized within the next few years, acidification is still an important threat for the lakes. Ongoing inflow of groundwater with high loads of products of pyrite oxidation (mainly sulphate and iron) into the lakes may cause so-called re-acidification after initially successful neutralization of the lake water (via reactions (3) and (4)). Concentrations of up to 3 g/L iron were found in groundwater in overburden dumps (Mansel et al., 2007). Re-acidification occurs if the inflow of acidity exceeds the stock of alkalinity of the lakes and its natural recharge (inflow of neutral and buffered water, internal production of alkalinity by iron and sulphate reduction). This may require continued or frequently repeated lake neutralization in the future, e.g. the continued addition of soda ash for Lake Bockwitz (Rönicke et al., this issue). Another option might be the permanent flushing of the respective lakes by neutral river water as has been done for Lake Senftenberg in the Lusatian lignite mining district since 1977 (Werner et al., 2001), given that rivers for permanent diversion of water are nearby and have appropriate water quality. About 20% of the pit lakes of the Central German lignite mining district are threatened by re-acidification, based on current knowledge. The time frame of potential re-acidification can be expected to be in a range similar to the natural neutralization of pit lakes without special measures as mentioned above.

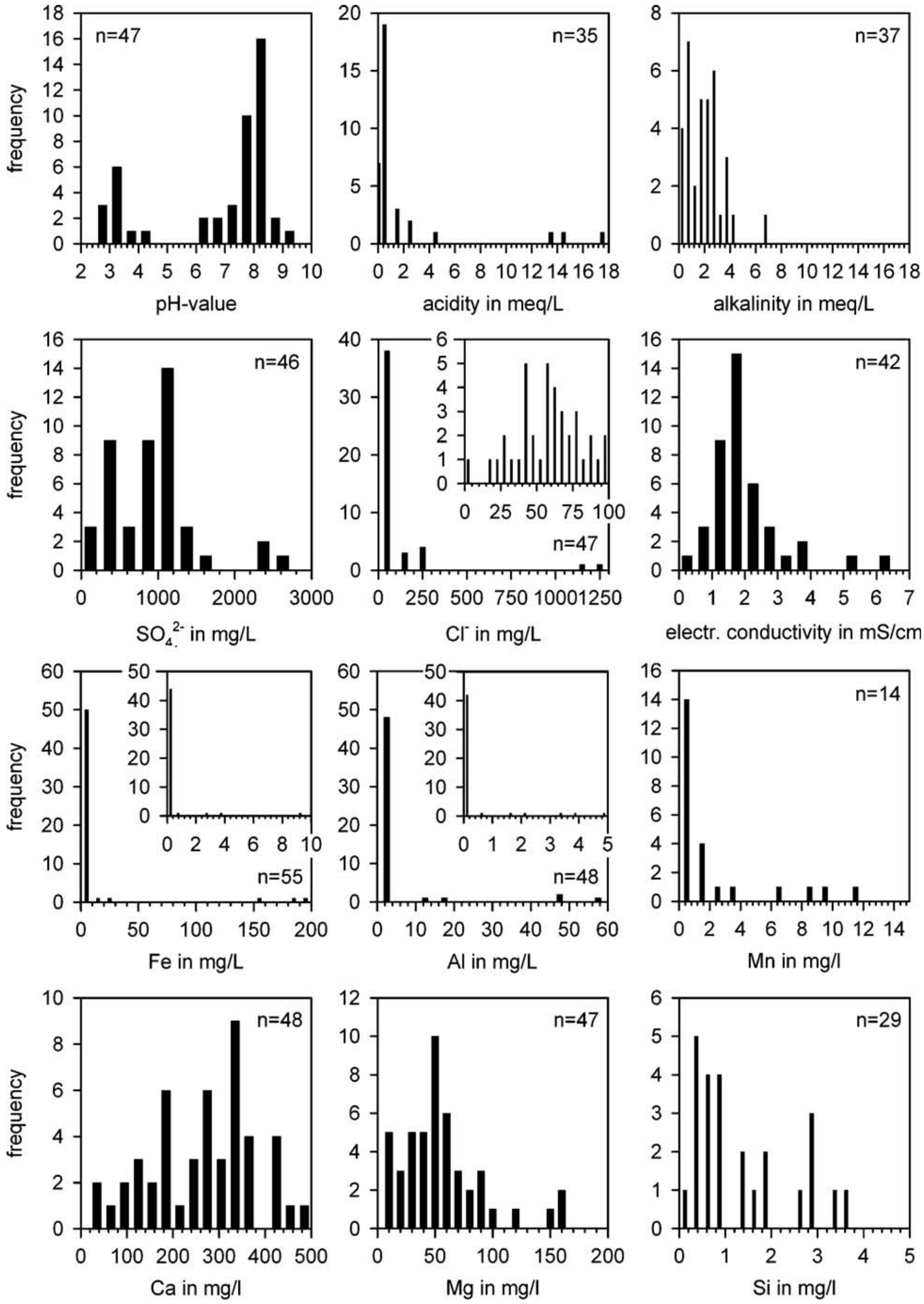

Fig. 4. Frequency distribution of chemical water properties related to acidification of the pit lakes in the Central German lignite mining district. Iron and manganese are given as total dissolved iron or manganese, respectively.

Acidity (detected by titration with 0.1 M NaOH to pH 8.2) and alkalinity (detected by titration with 0.1 M HCl to pH 4.3) indicate the degree of acidification present in spring 2007, or the buffering capacity of the lake waters insofar as they were neutral at that time, respectively, (Fig. 4). The alkalinity is usually low due to consumption of carbonates during neutralization and due to continuing inflow of acidity-bearing groundwater.

The concentrations of iron and aluminium also reflect the remaining acidification (Fig. 4). Higher concentrations are restricted to still-acid lakes or monimolimnia of meromictic lakes in the case of iron (not included in Fig. 4). However, iron still plays an important role for the water quality and its future development in the pit lakes because of its interaction with the phosphorus cycle in the lakes.

The manganese concentrations in the pit lakes are elevated under acid conditions but very low under neutral conditions (Fig. 4). Compared to the concentrations of iron and aluminium, the manganese concentrations are too low to make manganese an important contributor to acidity, even under acid conditions.

Calcium and magnesium concentrations reflect the consequences of buffering the acidity produced by pyrite oxidation (dissolution of carbonates, ion exchange, dissolution of silicates, etc.), the initial composition of minerals in the mined area and the source area of the current lake water (Fig. 4). Silicon concentrations are elevated in acid pit lakes (Fig. 4). Once the lake water is neutralized, silicon concentrations decrease, at least partially due to the improved living conditions for diatoms.

Sulphate is clearly the dominating anion in the lake water (Fig. 4). It results mainly from pyrite oxidation, even in lakes which were never acid. Its concentrations are high compared to waters not impacted by lignite mining in the region.

The higher concentrations of chloride are the result of the previously mentioned intrusion of saline groundwater (Fig. 4). As with iron, the monimolimnia of the meromictic lakes are not included in Fig. 4. The chloride concentrations in the monimolimnia of Lake Hufeisensee, Lake Wallendorf and Lake Rassnitz reach 8.8, 48.1 and 14.2 g/L, respectively.

The electrical conductivity indicates the generally relatively high concentrations of dissolved solids in the pit lake water, mainly sulphate, calcium and magnesium and, in the case of acid lakes with $pH < 2.8$, iron (Fig. 4). The highest values of electrical conductivity originate from the lakes, which are influenced by intrusion of saline groundwater. In these lakes, chloride and sodium dominate the electrical conductivity. The values of the monimolimnia of the meromictic examples of these lakes are again not included in Fig. 4.

Phosphorus concentrations of the lake water are low (Fig. 5), even in the case of filling with river water containing more than 100 μg/L of total phosphorus (TP). The relatively high concentration of iron in the lake sediment and in its pore water and the permanent import of iron with inflowing groundwater are the major reasons: the phosphorus is adsorbed onto the surfaces of precipitates of iron and buried in the sediment when the iron precipitates settle to the sediment (Duffek and Langner, 2002; Kleeberg and Grüneberg, 2005). According to the usually low phosphorus concentrations, the concentrations of chlorophyll a are also small (Fig. 5). As a consequence, in most German pit lakes eutrophication does not pose a risk to water quality requiring special measures and strategies (Lessmann et al., 2003; Schultze et al., 2005), in contrast to initial assumptions by Klapper and Schultze (1995). The only eutrophic pit lake is Lake Golpa IV in the Central German lignite mining district. In this case, eutrophication results from using the lake for intermediate storage of river water from the River Mulde for cooling purposes in a power plant over a period of decades (Hupfer et al., 1998).

The concentration of ammonium (Fig. 5) is often relatively high in acid pit lakes due to inhibition of nitrification (Prosser, 1987). The low concentrations of nitrate (Fig. 5) are the result of missing sources such as explosives or intense agriculture. Mining is done without blasting and intense agriculture is not common in the post-mining landscape of Central Germany due to limited fertility of the soils at the dump sites. Even in the case of filling with nitrate-bearing river water, rapid removal of nitrate from the lake water resulted in low nitrate concentrations after finishing input of river water. Primary production and denitrification in the lake sediment are suspected to be the most important processes for this removal. Although the water of the pit lakes is usually well oxygenated throughout the year (except the permanently anoxic monimolimnia of meromictic pit lakes), anoxic conditions were found to be common in pit lake sediments (Peine and Peiffer, 1998; Meier et al., 2004; Blodau, 2006).

The concentrations of dissolved organic carbon (DOC) are in the range of eutrophic natural lakes (3–34 mg/L; Thurman, 1985). Since the ranges of concentrations of phosphorus and chlorophyll a are low, the DOC found is probably not the result of autochthonous primary production. The DOC may originate from remains of lignite spread in the overburden dumps or in the aquifers which are feeding the pit lakes.

Trace contaminants are not presented in detail here. Heavy metals and trace elements mobilized due to acidification may reach considerable concentrations in acid pit lakes (Zn and Ni: < 500 μg/L; As, Cu, Cd, Cr and Pb: < 10 μg/L; Hg < 1 μg/L). Under neutral conditions, however, they are usually precipitating or removed by co-precipitation with iron or aluminium (Klapper and Schultze, 1995). Organic contamination of groundwater in the neighbourhood of Lake Goitsche did not affect the lake water quality due to changes in flow direction of the groundwater as a result of the flood event in 2002 (Wycisk et al., 2005). Contaminants leaving a waste deposit at the southern margin of

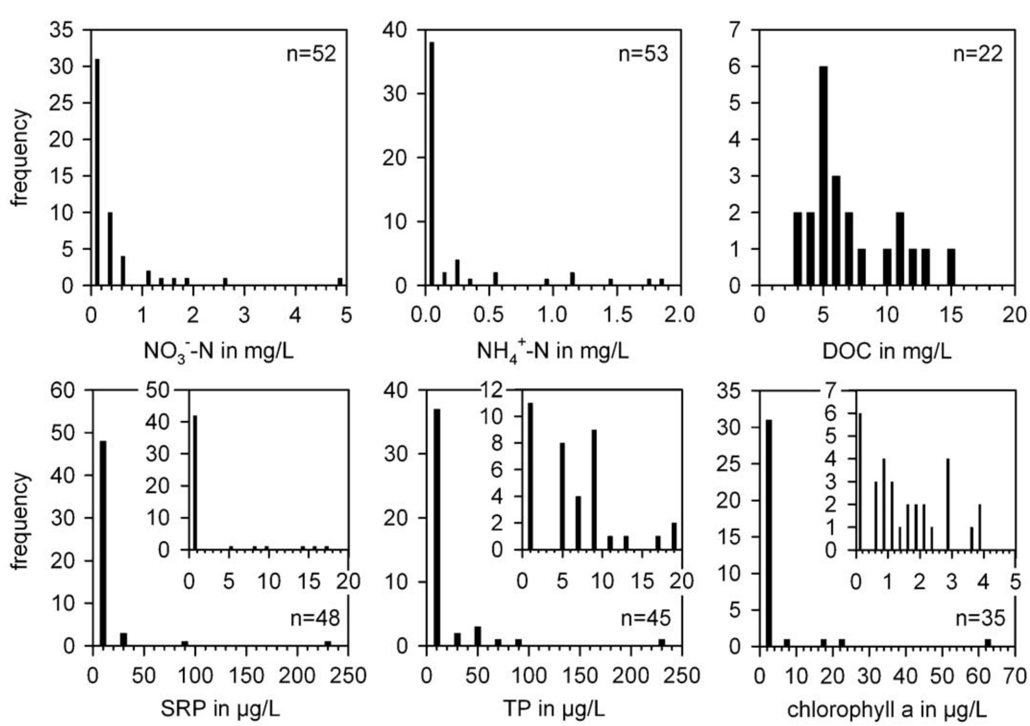

Fig. 5. Frequency distribution of concentrations of substances related to the biological productivity of the pit lakes in the Central German lignite mining district (SRP – soluble reactive phosphorus, TP – total phosphorus).

Lake Hufeisensee via groundwater are accumulated in the monimolimnion of the lake and the respective sediment (Stottmeister et al., 1999). Therefore, they do not affect the mixolimnion. Ammonium entering Lake Runstedt from the waste deposit at the lake bottom (>300 mg/L ammonium were found in the pore water of the waste) is oxidized by naturally occurring microbial communities in the lake. Hypolimnetic aeration was implemented in order to ensure the availability of sufficient oxygen. Lake Vollert Süd, its contaminants and its remediation were already described in the section on stratification. The enormous amounts of organic carbon originally restricted the Secchi depth to 3 cm (Stottmeister et al., 1999). Today, the mixolimnion of the lake has a good water quality. The contaminants are accumulated in the lake sediment and in the monimolimnion (Stottmeister, 2008).

Functioning of pit lakes in the landscape

Due to their total surface area of around 140 km^2 today, the sustainable use of the pit lakes is an important ecological and socio-economical factor for the Central German lignite mining district. Typical functions of lakes in a landscape are as habitat for aquatic and amphibian organisms, for larval stages of insects and for water fowl, as water source for wildlife, as geochemical sink and as providers of sites for human use, e.g. water-borne recreation, fishery, aquaculture, flood management and water storage.

The pit lakes of the Central German lignite mining district fulfil these functions widely, as indicated by their use. The major use of the pit lakes is for recreational purposes (Linke and Schiffer, 2002). The above-mentioned concern of infection, caused by the import of pathogens with river water, was found to be a much smaller risk than initially expected. Pathogens are removed from lake water relatively quickly by sedimentation, decay and dilution (Pusch et al., 2005; Wolf, 2005). Many lakes also became part of protected areas for nature conservation (e.g. Lake Rassnitz, Lake Paupitzsch, Lake Gremmin). A few lakes are used for fish breeding (e.g. the Muldereservoir). In the majority of the pit lakes, however, fishery is done only on the basis of the natural development of the fish community after an initial stocking. A few lakes are used for purposes of water management, mainly flood protection (e.g. Lake Borna, Lake Zwenkau after reaching planned water level). The function as geochemical sink is most impressive in the Muldereservoir due to the permanent through-flow of the complete River Mulde. It acts as a sink for heavy metals originating from abandoned ore mines in the Ore Mountains at the Czech-German border. In this way, the River Elbe is protected from strong contamination (Klemm et al., 2005).

Summary and lessons learned

Surface mining for lignite resulted in a new artificial lake district in the Central German lignite mining district which is poor in natural lakes. The pit lakes are an important part of the post-mining landscape and fulfil ecological as well as socio-economic functions. The major concern with respect to water quality, acidification resulting from mining-induced pyrite oxidation, has been managed successfully for the majority of the pit lakes. The filling with water from external sources, i.e., rivers or dewatering operations of mines still operating, was the most important strategy and by far the cheapest one (Höppner et al., 2006).

However, some lakes required additional or alternative measures in order to become neutral. The addition of soda ash and of lime at the lake surface was applied. The lessons learned from these treatments are that (i) a complete investigation and quantification of all sources of acidity is necessary for successful planning of neutralization, (ii) the parts of the underground which were aerated during mining or remain aerated in the long run in the immediate vicinity of the lakes may be a major source of acidity for a long time, and (iii) the wide spreading of the applied alkaline substances may improve the efficiency of neutralization (Neumann et al., 2008).

"Doing nothing", i.e., simply waiting for natural neutralization as in earlier times, is no longer accepted by the responsible authorities for new acid pit lakes or acid pit lakes having an outflow. Today, such a strategy is restricted to lakes which are not acidified.

Eutrophication, contamination with industrial hazardous substances and infection of lake water by pathogens via inflow of river water were found to be of low importance in the Central German lignite mining district. Salinization by intrusion of naturally saline groundwater is restricted to a few cases according to the geological conditions. The monimolimnia formed by the intruding saline groundwater act as sinks for phosphorus and other contaminants (Stottmeister et al., 1999; Schultze and Boehrer, 2008).

In some cases, the long-term inflow of acidifying groundwater from dump sites may result in re-acidification. Common treatment options (addition of alkaline substances, diversion of river water) may be applied in order to maintain the neutral state of the lakes, or new, more efficient options may be developed based on current research and scientific evaluation of the experiences made in Germany and worldwide (Schultze et al., 2009; Castendyk and Eary, 2009). However, further learning from past and current management practice for future management in Germany or other countries requires detailed documentation of applied methods, adequate monitoring of currently treated lakes and publication of results and lessons learned.

Acknowledgements

The study is kindly dedicated to Prof. Dr. W. Geller who promoted research on water quality of pit lakes during his work as head of the UFZ Department of Lake Research in Magdeburg, Germany from 1992 to 2008.

The Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV) and the Landestalsperrenverwaltung des Freistaates Sachsen (LTV) are acknowledged for providing data on water quality of many pit lakes. Kathleen Rogge is kindly acknowledged for her help in handling and analyzing data. Dr. Wolf von Tümpling made very helpful comments on an earlier version of this paper. The authors also wish to thank the reviewers for their comments, especially Prof. Dr. Devin Castendyk, whose very helpful comments considerably improved the paper.

References

Blodau, C., 2006. A review of acidity generation and consumption in acidic coal mine lakes and their watersheds. Sci. Total Env. 369, 307–332.

Boehrer, B., Schultze, M., Liefold, S., Behlau, G., Rahn, K., Frimel, S., Kiwel, U., Kuehn, B., Brookland, I., Büttner, O., 2003. Stratification of mining Lake Goitsche during flooding with river water. In: Tailings and Mine Waste '03. Swets & Zeitlinger, Lisse, pp. 223–231.

Castendyk, D.N., Eary, L.E. (Eds.), 2009. Management Technologies for Metal Mining Influenced Water, vol. 3 – Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability. Society for Mining, Metallurgy, and Exploration, Littleton.

Doyle, G.A., Runnells, D.D., 1997. Physical limnology of existing mine pit lakes. Min. Eng. 49, 76–80.

Duffek, A., Langner, C., 2002. P retention in an acidic mining lake under the influence of flooding with river water. Verh. Internat. Verein. Limnol. 28, 1717–1720.
Eissmann, L., 2002a. Tertiary geology of the Saale-Elbe Region. Quat. Sci. Rev. 21, 1245–1274.
Eissmann, L., 2002b. Quaternary geology of eastern Germany (Saxony, Saxon-Anhalt, South Brandenburg, Thuringia), type area of the Elsterian and Saalian Stages in Europe. Quat. Sci. Rev. 21, 1275–1346.
Evangelou, V.P., 1995. Pyrite Oxidation and its Control. CRC Press, Boca Raton.
Heidenreich, H., Boehrer, B., Kater, R., Henning, G., 1999. Gekoppelte Modellierung geohydraulischer und limnophysikalischer Vorgänge in Tagebaurestseen und ihrer Umgebung. Grundwasser 4, 49–54.
Höppner, S., Rieger, K., Scholz, G., 2006. Wirtschaftliche Bewertung innovativer, aktiver und passiver Wasseraufbereitungssysteme für saure Bergbaugewässer. In: Merkel, B., Schaeben, H., Wolkersdorfer, C., Hasche-Berger, A. (Eds.), Behandlungstechnologien für bergbaubeeinflusste Wässer + GIS-Geowissenschaftliche Anwendungen und Entwicklungen. Wiss. Mitt. Inst. f. Geologie Nr 31/2006. TU Bergakademie Freiberg, Freiberg, pp. 105–112.
Hoth, N., Feldmann, H., Rinker, A., Glombitza, F., Häfner, F., 2005. Reductive processes within lignite dumps – chance of a long-term natural attenuation process. Geoderma 129, 19–31.
Hupfer, M., Fischer, P., Friese, K., 1998. Phosphorus retention mechanisms in the sediment of a eutrophic mining lake. Water Air Soil Pollut. 108, 341–352.
Jolas, P., 1998. Utilization of drainage water to fill residual lakes. BRAUNKOHLE – Surf. Min. 50, 337–345.
Jordan, H., Weder, H.-J., 1995. Hydrogeologie – Grundlagen und Methoden. F. Enke Verlag, Stuttgart.
Junge, F.W., Jendryschik, K., 2003. Investigations into the distribution of element concentrations in a recent dam and their seasonal and hydrographical correlation (Bitterfelder Muldestausee, Saxony-Anhalt). Acta Hydrochim. Hydrobiol. 31, 378–390.
Klapper, H., Schultze, M., 1995. Geogenically acidified mining lakes – living conditions and possibilities of restoration. Int. Rev. ges. Hydrobiol. 80, 639–653.
Kleeberg, A., Grüneberg, B., 2005. Phosphorus mobility in sediments of acid mining lakes, Lusatia, Germany. Ecol. Eng. 24, 89–100.
Klemm, W., Greif, A., Broeckaert, J.A.C., Siemens, V., Junge, F.W., van der Veen, A., Schultze, M., Duffek, A., 2005. A study on arsenic and the heavy metals in the Mulde River system. Acta Hydrochim. Hydrobiol. 33, 475–491.
Krüger, B., Kadler, A., Fischer, M., 2002. The creation of post-mining landscapes of lignite mining in the new federal states. Surf. Min. – Braunkohle other miner. 54, 161–169.
Lessmann, D., Uhlmann, W., Grünewald, U., Nixdorf, B., 2003. Sustainability of the flooding of lignite mining lakes as a remediation technique against acidification in the Lusatian mining district, Germany. In: Farell, T., Taylor, G. (Eds.), Proceedings of the 6th International Conference on Acid Rock Drainage (Cairns, Queensland, July 14–17, 2003). The Australian Institute of Mining and Metallurgy Publication Series No 3/2003. The Australian Institute of Mining and Metallurgy, Carlton Victoria, pp. 521–527.
Linke, S., Schiffer, L., 2002. Development prospects for the post-mining landscape in Central Germany. In: Mudroch, A., Stottmeister, U., Kennedy, C., Klapper, H. (Eds.), Remediation of Abandoned Surface Coal Mining Sites. Springer, Berlin, pp. 111–145.
Litt, T., Wansa, S., 2008. Quartär. In: Bachmann, G.H., Ehling, B.-C., Eichner, R., Schwab, M. (Eds.), Geologie von Sachsen-Anhalt. E. Schweizerbart'sche Verlagsbuchhandlung, Suttgart, pp. 293–325.
LMBV, 2008. Sanierungsbericht 2007. Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft, Senftenberg.
Mansel, H., Büttcher, H., Tienz, B.-S., Jolas, P., 2007. Exfiltration eisenbelasteter Grundwässer in die Pleiße südlich von Leipzig - Ergebnisse einer vorbereitenden Studie. In: Drebenstedt, C., Struzina, M. (Eds.), Management bergbaubedingten Säurepotenzials. Institut f. Bergbau und Spezialtiefbau der TU Bergakademie Freiberg, pp. 155–165.
Meier, J., Babenzien, H.-D., Wendt-Potthoff, K., 2004. Microbial cycling of iron and sulfur in sediments of acidic and pH-neutral mining lakes in Lusatia (Brandenburg, Germany). Biogeochemistry 67, 135–156.
Neumann, V., Nitsche, C., Pokrandt, K.-H., Tienz, B.-S., 2008. Quantifizierung des Aziditätsstroms in einen neutralisierten Tagebausee zu Beginn der Nachsorge. In: Merkel, B., Schaeben, H., Hasche-Berger, A. (Eds.), Behandlungstechnologien für bergbaubeeinflusste Wässer + GIS-Geowissenschaftliche Anwendungen und Entwicklungen. Wiss. Mitt. Inst. f. Geologie Nr. 37/2008. TU Bergakademie Freiberg, Freiberg, pp. 73–80.
Nixdorf, B., Hemm, M., Schlundt, A., Kapfer, M., Krumbeck, H., 2001. Braunkohlentagebauseen in Deutschland: Gegenwärtiger Kenntnisstand über wasserwirtschaftliche Belange von Braunkohlentagebaurestlöchern. UBA-Texte 35-01. Umweltbundesamt, Berlin.
Peine, A., Peiffer, S., 1998. In-lake neutralization of acid mine lakes. In: Geller, W., Klapper, H., Salomons, W. (Eds.), Acidic Mining Lakes. Springer-Verlag, Berlin, pp. 47–64.
Prosser, J.I., 1987. In: Nitrification. IRL Press, Oxford.
Pusch, D., Oh, D.-Y., Wolf, S., Dumke, R., Schröter-Bosin, U., Höhne, M., Röske, I., Schreier, E., 2005. Detection of enteric viruses and bacterial indicators in German environmental waters. Arch. Virol. 150, 9292–9947.
Rönicke, H., Schultze, M., Nitsche, C., Neumann, V., Tittel, J., 2010. Changes of the plankton community composition during chemical neutralisation of pit lake Bockwitz. Limnologica, 40, this issue, doi:10.1016/j.limno.2009.11.05.
Sanchez Espana, J., Lopez Pamo, E., Santofimia Pastor, E., Diez Ercilla, M., 2008. The acidic mine pit lakes of the Iberian Pyrite Belt: an approach to their physical limnology and hydrogeochemistry. Appl. Geochem. 23, 1260–1287.
Schultze, M., Boehrer, B., 2008. Development of two Meromictic Pit Lakes – a case study from the Former Lignite Mine Merseburg-Ost, Germany. In: Rapantova, N., Hrkal, Z. (Eds.), Mine Water and the Environment – Proceedings of the 10th IMWA Congress, 2–5 June, 2008 Karlovy Vary, Czech Republic. VSB-Technical University of Ostrava, Faculty of Mining and Geology, Ostrava, pp. 611–614.
Schultze, M., Boehrer, B., Duffek, A., Herzsprung, P., Geller, W., 2005. Introduction of river water as a tool to manage water quality in pit lakes. In: Loredo, J., Pendas, F. (Eds.), Proceedings of the 9th International Mine Water Association Congress, September 5–7, 2005, Oviedo, Spain. Departemento de Explotacion y Prospeccion de Minas, University of Oviedo, Oviedo, pp. 273–279.
Schultze, M., Geller, W., Wendt-Potthoff, K., Benthaus, F.-C., 2009. Management of German pit lakes. In: Öhlander, B. et al. (Eds.), Proceedings of Securing the Future and 8th ICARD, June 23–26, 2009, Skellefteå, Sweden, 〈http://www.proceedings-stfandicard-2009.com.〉.
Shevenell, L., Connors, K.A., Henry, C.D., 1999. Controls on pit lake water quality at sixteen open-pit mines in Nevada. Appl. Geochem. 14, 669–687.
Stottmeister, U., 2008. Altlastensanierung mit Huminstoffsystemen. Chem. Unserer Zeit 42, 24–41.
Stottmeister, U., Weißbrodt, E., Becker, P.M., Pörschmann, J., Kopinke, F.D., Martius, G.G.M., Wießner, A., Kenedy, C., 1998. Analysis, behaviour and fate of a lignite pyrolysis wastewater deposit, Contaminated Soil '98. Thomas Telford Publishing, London.
Stottmeister, U., Glässer, W., Klapper, H., Weissbrot, E., Eccarius, B., Kennedy, C., Schultze, M., Wendt-Potthoff, K., Frömmichen, R., Schreck, P., Strauch, G., 1999. Strategies for remediation of former opencast mining areas in eastern Germany. In: Azcue, J.M. (Ed.), Environmental Impacts of Mining Activities: Emphasis on Mitigation and Remediation. Springer-Verlag, Berlin, pp. 263–296.
Stumm, W., Morgan, J.J., 1996. Aquatic Chemistry – Chemical Equilibria and Rates in Natural Waters. 3rd edition, John Wiley and Sons, New York.
Thurman, E.M., 1985. Organic geochemistry of natural waters, Martinus Nijhoff/Dr. W. Junk Publishers, Dordrecht.
Trettin, R., Gläßer, W., Lerche, I., Seelig, U., Treutler, H.-C., 2006. Flooding of lignite mines: isotope variations and processes in a system influenced by saline groundwater. Isot. Environ. Health Stud. 42, 159–179.
Trettin, R., Gläser, H.R., Schultze, M., Strauch, G., 2007. Sulfur isotope studies to quantify sulfate components in water of flooded lignite open pits – Lake Goitsche, Germany. Appl. Geochem. 22, 69–89.
Werner, F., Bilek, F., Luckner, L., 2001. Impact of regional groundwater flow on the water quality of an old post-mining lake. Ecol. Eng. 17, 133–142.
Wolf, S., 2005. Evaluierung der hygienischen Wasserqualität unter besonderer Berücksichtigung von Bakteriophagen am Beispiel eines Tagebausees. Ph.D. thesis, Technical University Dresden.
Wycisk, P., Neumann, C., Gossel, W., 2005. Flooding induced effects from the Mining Lake Goitzsche on groundwater and land-use in the Bitterfeld area. Acta Hydrochim. Hdrobiol. 33, 507–518.
Zschiedrich, K., Benthaus, F.-C., Dahlke, M., 2007. Flutung und Bewirtschaftung von Bergbaufolgeseen. In: Drebenstedt, C., Struzina, M. (Eds.), Management bergbaubedingten Säurepotentials. Inst. f. Bergbau und Spezialtiefbau der TU Bergakademie Freiberg, Freiberg, pp. 166–174.