Introduction of river water as a tool to manage water quality in pit lakes

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ABSTRACT
The filling of pit lakes is often accelerated to minimize acidification, to stabilize the sidewalls of the former mine pit, and to make the lakes available for public use as fast as possible. Rivers are the major sources of filling water. In addition, the permanent flushing of pit lakes with river water may be an option to abate acidification and its consequences. However, the use of river water is often accompanied by the risk of eutrophication due to the water quality in the rivers. Our central demonstration object is Lake Goitsche near Bitterfeld in Germany. The void originates from former lignite mining, which was filled with water from River Mulde from 1999 to 2002. The initially acidic lake water was successfully neutralized. The high amounts of phosphorus introduced with the river water did not cause eutrophication but were bound in the lake sediment. The comparison with other lignite mining lakes indicates, that the very good experiences from Lake Goitsche cannot be transferred to every other pit lake. There may be a risk of long-term re-acidification and of temporary or long-term eutrophication in certain cases.

INTRODUCTION
In Germany, pit lakes resulting from lignite surface mining remarkably contribute to the total number of lakes. In recent years 120 new lakes have been created (Krüger et al. 2002). The majority of these lakes are filled with river water (Luckner et al. 1996, Haferkorn et al. 1999). In some years, about one third of the bigger lakes will or iginate from lignite mining (Figure 1). More than 500 lakes will then exist in Germany which originates from lignite mining.

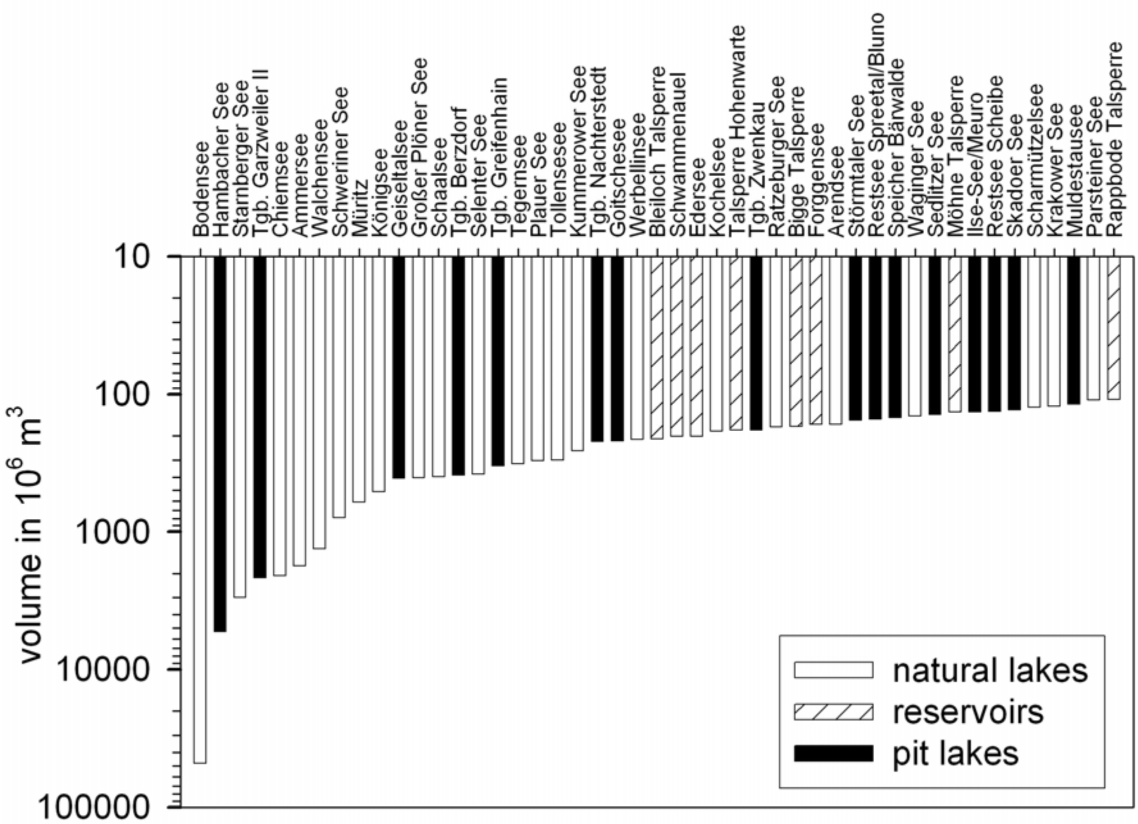

Figure 1: The 46 largest lakes in Germany ranked by volume (including recent and future pit lakes; after Schultze et al. 1999, Nixdorf et al. 2001)

Also in the Czech Republic and in Poland lakes result from lignite mining (Stottmeister et al. 2002). In other countries, the awareness for pit lakes, which often originate from ore mining, grows too (Davis & Ashenberg 1989, Miller et al. 1996, Eary 1999, Parshley & Bowell 2003). With respect to water quality Klapper & Schultze (1995) point at the following major aspects of concern:

- acidification as the consequence of the oxidation of pyrite or other sulphide minerals
- eutrophication as a consequence of high nutrient import from inflowing contaminated river water or non-adequate use of the lakes
- contamination with trace contaminants by contaminated river water, neighbouring waste deposits (e.g. tailings and industrial or municipal landfills)
- salinization by the intrusion of highly saline water from natural salt deposits
- infection by pathogens from river water which is contaminated with waste water or from non-adequate use of the lakes

Providing there is enough river water available (see also Luckner & Eichhorn 1996, Schlaeger et al. 2003, Koch et al. 2005), there are two options for using it to abate acidification:

- exclusive use of river water for the primary filling of pit lakes
- permanent flushing of pit lakes by river water

This study is focused on the successful use of river water to abate acidification and the eutrophying effect of river water in pit lakes. A number of case studies are comprised to draw generalized conclusions.

Goals of the diversion of river water

The major goal of primary filling of a mining void with river water is to fill the void as fast as possible. In this way the slopes of the former mine can be protected from the destruction by inflowing ground water if the water level in the rising lake is higher than ground water level in the surrounding aquifers. Additionally, a fast rising water level protects the slopes from erosion by rain, melting snow and gradual impact of waves. Consequently, the slopes can be formed steeper. This lowers the costs for preparing the slopes. Further goals of fast filling of pit lakes with river water are the earlier usability of the lakes and the abatement of acidification.

The permanent diversion of river water into already existing pit lakes can have various purposes. The lakes may be used as reservoirs. Pit lakes become easier accessible for water tourism through a permanent connection with the river network. Last but not least, acidification may be prevented by permanent flushing.

In some cases, the permanent connection of rivers to pit lakes may simply result from the topologic settings.

The aspect of neutralization

For the successful neutralization with river water the following points need to be considered:

- import of alkalinity with the river water
- import of acidity with the river water
- dilution of the water already present in the pit lake
- replacement of water present in a pit lake
- import of acidity and/or alkalinity by erosion and elution of the former mine slopes and the shore
- land slides at the former mine slopes
- reductive microbial processes
- compaction of lake sediment and liberation of acidity during the transformation of hydroxosulphates to hydroxides (e.g. schwertmannite to goethite)

The aspect of eutrophication

In inland waters normally phosphorus is the most important nutrient for eutrophication. Its availability is the crucial factor (Marsden 1989). The following processes are important:

- import of phosphorus with inflowing river water
- import of phosphorus with inflowing ground water
- transformations of phosphorus in the lake water
- binding of phosphorus in the lake sediment

CASE STUDIES

The cases discussed in the following paragraphs are only pit lakes in the eastern part of Germany which originate from lignite mining. Table 1 gives an overview over the selected lakes, their most important morphometric data, their history, their connection to river systems and their use. Figure 2 shows the location of the lakes.

Table 1: Characteristics of pit lakes (* median for the used river water during the given period; data sources: [1] Sensel 1997, [2] LUA, [3] Haferkorn et al. 1999, [4] LMBV)

	Lake and morphometric data	Filling and filling water quality	Use and special remarks
1	Senftenberger See area[1] 1100 ha volume[1] $80*10^6$ m^3 max. depth[1] 23 m	• ground water and water from river Schwarze Elster since 1968 • permanent inflow of a part of river Schwarze Elster since 1976 • Alk: 1,25 mmol/l (1998-2002)*[2] • TP: 0,11 mg/l (1998-2002)*[2]	• recreation • interruption of inflow of river water in 1994 + 1995
2	Goitschesee area[3] 1332 ha volume[3] $213*10^6$ m^3 max. depth[3] 47 m	• water from river Mulde 05/1999-07/2002 • flood disaster in August 2002 (inflow >$90*10^6$ m^3) • Alk: 1,3 mmol/l (1999-2001)* • TP: 0,11 mg/l (1999-2001)*	• recreation • nature conservation • reduction of water level after flood disaster
3	Seelhäuser See area[3] 622 ha volume[3] 74*106 m^3 max. depth[3] 28 m	• water from river Mulde 07/2000-05/2005 • flood disaster in August 2002 (inflow $9,3*10^6$ m^3) • Alk: 1,4 mmol/l (2000-2002)*[4] • TP: 0,16 mg/l (2000-2002)*[4]	• planned: recreation

Table 1: continued

	Lake and morphometric data	Filling and filling water quality	Use and special remarks
4	Golpa-Nord area[3] 544 ha volume[3] 67*106 m^3 max. depth[3] 33 m	• water from river Mulde since 01/2000 • Alk: 1,3 mmol/l (2000-2002)*[4] • TP: 0,12 mg/l (2000-2002)*[4]	• planned: recreation
5	Delitzsch-Südwest area[3] 441 ha volume[3] $43*10^6$ m^3 max. depth[3] 36 m	• water from river Weiße Elster since 12/1998 • Alk: 2,1 mmol/l (1999-2002)*[4] • TP: 0,15 mg/l (1999-2002)*[4]	• planned: recreation
6	Merseburg-Ost 1a area[3] 338 ha volume[3] $36*10^6$ m^3 max. depth[3] 28 m	• water from river Weiße Elster 08/1998-07/2000 • Alk: 2,7 mmol/l (1998-2000)*[4] • TP: 0,13 mg/l (1998-2000)*[4]	• nature conservation • meromictic
7	Merseburg-Ost 1b area[3] 310 ha volume[3] $66*10^6$ m^3 max. depth[3] 37 m	• water from river Weiße Elster 03/1998-07/2000 • Alk: 2,7 mmol/l (1998-2000)*[4] • TP: 0,13 mg/l (1998-2000)*[4]	• recreation • meromictic
8	Runstädter See area[3] 230 ha volume[3] $55*10^6$ m^3 max. depth[3] 33 m	• water from river Saale 08/1998-07/2000 • Alk: 3,1 mmol/l (2001-2002)*[4] • TP: 0,08 mg/l (2001-2002)*[4]	• no use • industrial waste deposit on the lake bottom (ashes, wastes of $(NH_4)_2SO_4$-production)

Senftenberger See

In the public, Senftenberger See was seen as an excellent example for the success of diversion of river water into pit lakes as a management tool to get a good water quality and for the successful conversion from an open cast mine to a centre for recreation and tourism. But a closer view shows that Senftenberger See is indicating clearly the limits of the management tool "diversion of river water". Figure 3 shows the pH and the water level from the start of the filling until 1997.

Sensel (1997) pointed out that already during the primary filling of the lake water from river Schwarze Elster was diverted into the rising acidic lake. But neutralization was not reached during that period. According to Sensel (1997) there are the following reasons: a stock of too much acidity in the lake when the diversion of river water was started, import of acidity caused by land slides and ongoing inflow of acidifying ground water. The neutralization of the northern basin (about 1150 ha) happened some years after the primary filling. It was the result of permanent lake flushing by diverted river water. Intermittent discontinuation of river water inflow caused temporary re-acidification in the subsequent period (Werner 1999; Figure 3). The southern basin of the lake (about 150 ha) has never been neutralized as it is separated from the northern basin by an island (a former overburden dump) and flushing through through the remaining shallow channels, which are densely colonised by macrophytes, is not efficient enough.

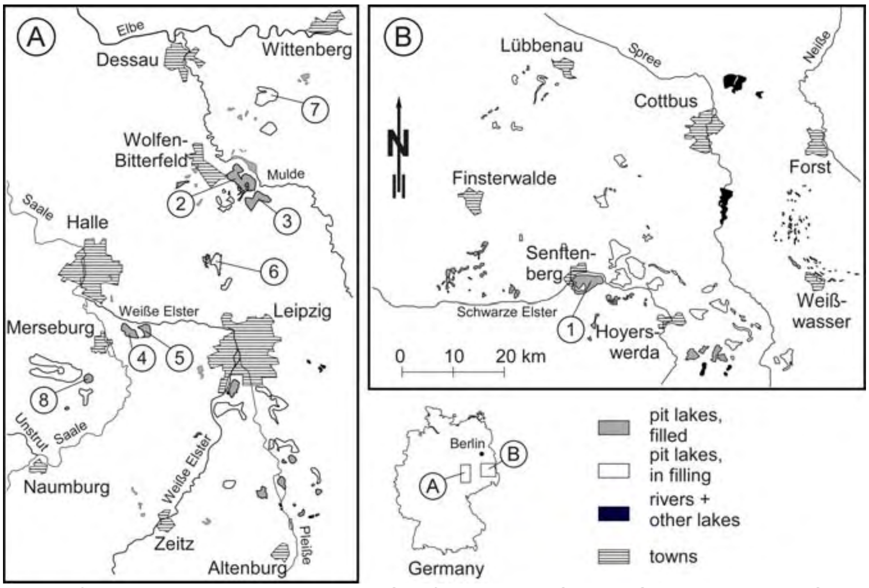

Figure 2: Location of the compared pit lakes. 1-Senftenberger See, 2-Goitschesee, 3-Seelhäuser See, 4-Merseburg-Ost 1a, 5-Merseburg-Ost 1b, 6-Delitzsch-Südwest, 7-Golpa-Nord, 8-Runstädter See

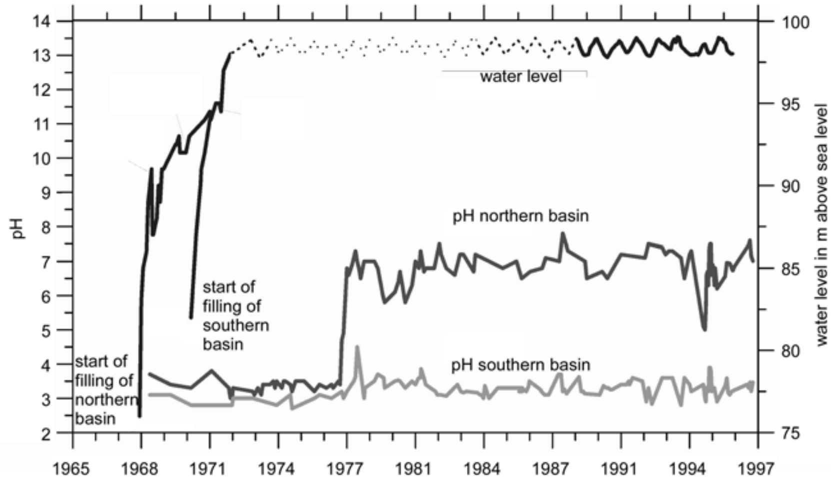

Figure 3: pH and water level in the basins of lake Senftenberger See (redrawn from Werner 1999)

For the future the re-acidification of the whole lake cannot be excluded because of changes in the regional ground water flow. Former lignite mines in the north of lake Senftenberger See have been filled in recent years and cause an increasing inflow of acidifying ground water. Intense research activities are undertaken to find new strategies to prevent a complete re-acidification (Schöpke & Koch 2002).

Lake Goitsche

Lake Goitsche near Bitterfeld consists of three sub-basins called Mühlbeck, Niemegk and Döbern. When the filling with river water was started in May 1999 the sub-basins Mühlbeck and Niemegk had small acidic precursor lakes on their bottom. The small precursor lake in sub-basin Döbern was neutral due to locally differing geological conditions (Kringel et al. 2000, Grützmacher et al. 2001).

After only 6 weeks of inflowing river water, the epilimnion of sub-basin Mühlbeck was neutralized. At the end of August 1999 the hypolimnion was neutralized too as a consequence of a complete overturn. In sub-basin Niemegk the neutralization of the epilimnion happened in June 2000. The hypolimnion was neutralized during the complete overturn in January 2001. Sub-basin Döbern was acidified temporarily since February 2000 due to the inflow of acidic water from the epilimnion of sub-basin Niemegk. In summer 2000, the epilimnion of sub-basin Döbern was neutralized after the epilimnion of sub-basin Niemegk had been neutralized. The hypolimnion was neutralized during the overturn in January 2001 as in sub-basin Niemegk. A detailed description of the filling, the chemical stratification and the neutralization is given in Boehrer et al. (2003).

Figure 4 is illustrating the described development as balances of alkalinity and acidity for the sub-basins at selected dates. The most interesting development can be seen in sub-basin Niemegk. From June to September 1999 the amount of acidity in this sub-basin was increasing although the inflowing water from sub-basin Mühlbeck was neutral. This was the result of erosion and elution of the former mine bottom where the Bitterfelder amber-bearing sequence is situated. This sequence is the main source of pyrite in the former mine Goitsche (Kringel et al. 2000, Grützmacher et al. 2001). Aeration during mining operations and during reclamation before filling with water resulted in intense pyrite oxidation and made this material to be the main source of acidity of the rising lake Goitschesee. During summer it was washed out by waves and erosion along the rising water line. At the end of summer 1999, this material was covered completely with water. The slopes of the former mine Goitsche were stabilized by placing quaternary soil in front of the slopes to make the slopes less steep during mine reclamation before filling with water. This soil is naturally containing carbonates but no pyrite (Grützmacher et al. 2001). The erosion and elution of these soils at the sidewalls during the further filling from autumn 1999 to summer 2000 caused an increased rate of neutralization. This rate was remarkably higher than the complete import of alkalinity by inflowing river water until summer 2000.

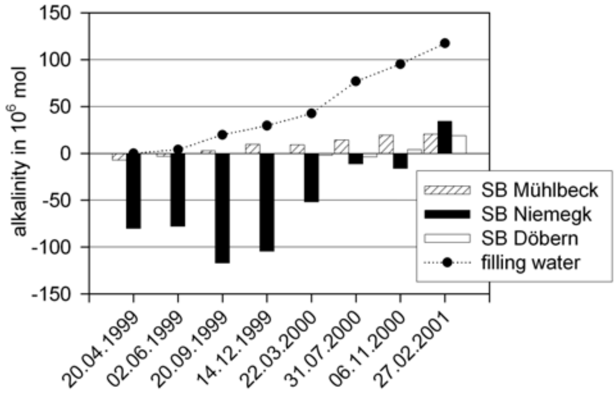

Figure 4: Stocks of alkalinity in lake Goitschesee at selected dates during filling and total import of alkalinity with river water. Negative values indicate remaining stocks of acidity. (SB – sub-basin)

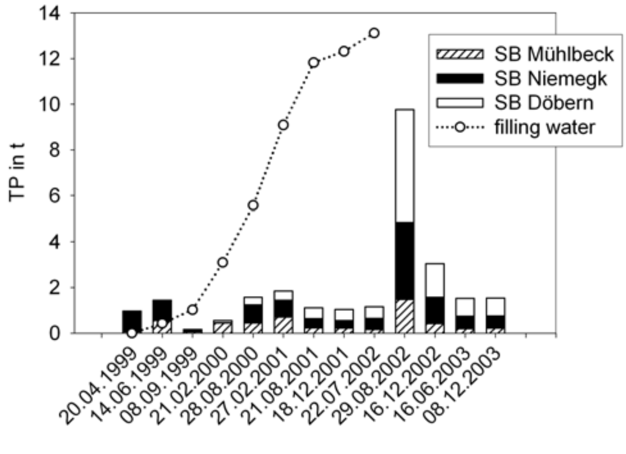

Figure 5: Stocks of total phosphorus (TP) in Lake Goitsche at selected dates and total import of phosphorus with river water (only until the flood disaster in August 2002 because of the lack of exact data on water inflow during the flood; SB – sub-basin)

More than 95% of the phosphorus imported into Lake Goitsche with the river water was deposited in the lake sediment (Figure 5). According to the progress of neutralization first the binding to iron was dominating, then to aluminium and after neutralization again to iron (Duffek & Langner 2002). The high efficiency of removal of phosphorus after the neutralization was surprising because there were nearly no iron nor aluminium available in the water body of Lake Goitsche in that period. Even the enormous import of phosphorus during a flood disaster in August 2002 (inflow of more than $90*10^6$ m^3 within some days) was removed rapidly from the lake water. The incorporation of phosphorus into the biomass of diatoms and their fast sedimentation after small blooms in spring 2001, 2002, and 2003 and in autumn 2002 seemed to contribute remarkably to the sedimentation of the phosphorus. The recent concentration of total phosphorus in the lake water is in the range of 10 µg/l.

I.e., Lake Goitsche is ologotrophic to mesotrophic. In connection with the neutralization the filling of Lake Goitsche can be seen as a good example of successful use of river water for the primary filling of a pit lake. Caused by the local geologic conditions there is no risk of re-acidification. The further diversion of river water as a management tool is not planned and not necessary.

Seelhäuser See
This lake was filled first by intended diversion of water from river Mulde. Alike Lake Goitsche it was also affected by the flood disaster in August 2002, but in a much lesser extend. The neutralization happened as a consequence of the flood. A re-acidification is not feared And the flood waters did not cause eutrofication. The lake is still mesotrophic.

Lakes Merseburg-Ost
Both lakes in the former mine Merseburg-Ost are meromictic, i.e. show permanent chemical stratification, due to the intrusion of highly saline ground water from the deeper underground (Heidenreich et al. 1999). Both lakes never were acidic although there are inflows of acidic ground water (Trettin et al. 1999). The balance between import of acidity and of alkalinity always showed an excess of alkalinity. The import of phosphorus by the river water used for filling in 1998, 1999 and 2000 did not result in eutrophication. The phosphorus was deposited in the sediment and accumulated in the monimolimnion (water body at the bottom of the lake which is excluded from the seasonal overturn). The lakes are mesotrophic. A future acidification is not likely.

Lake Delitzsch-Südwest
This lake was never acidic although the elevated sulphate and iron concentrations of springs in the former slopes of the mine indicated the occurrence of pyrite oxidation. A future acidification is not expected. The river water was diverted from river Weiße Elster with high phosphorus concentration as it was diverted near the waste water treatement plant of the city of Leipzig. The phosphorus concentrations in the lake varied between 20 µg/l and 30 µg/l but reached sometimes values of about 80 µg/l. I.e., the lake is mesotrophic to eutrophic.

Lake Golpa-Nord
The situation lake Golpa-Nord is similar to that in Lake Delitzsch-Südwest. There was no acidification despite the occurrence of pyrite oxidation. The phosphorus concentrations in the lake are varying in nearly the same range causing the same level of trophic level: mesotrophic to eutrophic.

Runstädter See
The former mining void Großkayna was used as disposal site for ashes and other wastes of the nearby chemical industry. A waste dump with a maximum thickness of about 20 m was created from the late 60s to the early 90s. The major mobile contaminant in this dump is ammonium with concentrations >300 mg/l in the pore water of the waste dump. The exchange between dump and lake is recently driven by diffusion. For the future a ground water inflow is expected across the waste dump. As indicated by relatively low sulphate and iron concentrations in the ground water pyrite oxidation does not play a remarkable role in the environment of this lake. Acidification caused by pyrite oxidation is consequently not relevant.
Phosphorus concentration in Lake Runstädter See was in the range of the filling river water. When the filling was completed the phosphorus concentration decreased slowly e.g. due to incorporation into biomass – sedimentation of detritus – partly recycling of phosphorus during the early diagenesis of the sediments, resulting in slow net-sedimentation of phosphorus. The lake is recently developing from a eutrophic towards a mesotrophic state which is the most likely long-term state of Runstädter See.

CONCLUSIONS
The results indicate the filling of pit lakes with river water as a viable way to achieve good water quality. The progress of neutralization is strongly influenced by stratification of the water body and by erosion and elution of the soils of the former mine pit. Senftenberger See demonstrates that neutralization can fail during primary filling. Also the reliability of neutralization by permanent inflow of river water into pit lakes may be limited.
The majority of examples indicate no relevant eutrophication risk during primary filling. The likelihood of recycling of the phosphorus deposited in the sediments is low because of the good availability of iron. Nevertheless there is a risk of eutrophication caused by long-term inflow of river water (Hupfer et al. 1998) and by inappropriate use of the lakes (Axler et al. 1996).

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