Innovative Mine Water Treatment in Post-Mining-Areas of Germany

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Abstract The lignite mining dominated landscape in the Lausitz and Leipzig district is characterized by a vast mined-out area which includes 240 km^2 pit lakes. The groundwater depression cone covers an area of about 2100 km^2 at the Lausitz, and 1200 km^2 in the Leipzig district. Water treatment is required either for the lake water bodies or the discharge waters. Besides conventional liming, development work is carried out on test implementation with soda ash. Alkalinity losses have been recognized due to sediment exchange. Innovative technologies are developed for *in situ* aquifer treatment by microbial sulfate reduction, resulting in a 40 % sulfate reduction as well as a 90 % iron reduction. Future development is to be carried out in the groundwater flow alongside a river bank.

Keywords Innovative treatment, soda ash, microbial sulfate reduction

Introduction

In the Lausitz and Leipzig mining areas lignite extraction resulted in about 50 large open mine pits as well as about 200 smaller residual openings. Open cast mining is actually the most efficient method of extracting lignite, which is located in shallow depth in tertiary and quartery layers of sand, clay and gravel. But this has a severe impact on the surface and on groundwater: the mining dominated landscape in the Lausitz area is for example characterized by 800 km^2 of mined-out area, followed by vast dump areas as well as 140 km^2 pit lakes (Fig. 1). The groundwater depression cone covers an area of about 2100 km^2.

Surface and groundwaters are affected by acid mine drainage (AMD). The generally accepted aim of remediation is the recovery of surface and groundwaters, balanced to a nearly stable level as well as reducing long lasting AMD.

In order to achieve a balanced system of end lakes, these lakes have been flooded with 3.8 Gm^3 water diverted from nearby rivers, ongoing mines and groundwater inflow since 1995. The remediation aims to convert the water quality from pH values 2 or 3 to values between 6 and 8. A decrease of dissolved aluminum and iron as well as a decrease of sulphate concentration below the level of corrosion is important in order to eliminate the human threshold for health and ecological problems. In general, dissolved iron is not toxic to humans, but causes ochre precipitation along the outflow to surface streams and reduce biological life within these streams.

To optimize this flooding process, the forecast of water quality development is inevitable. Based on ground- and surface water modeling, hydro chemical calculations are carried out to predict the amount of acidity which has to be treated during the neutralization process as well as sulphate and iron reduction along the lifespan of the lake.

Mine water treatment

Flooding with surface waters from nearby rivers is considered the most effective way to stabilize the water household by means of quantity and quality. Adding alkaline substances is the traditional method of mine water treatment used in German pit lakes (Geller *et al.* 2012). The first time such treatment took place was at lake Senftenberg (1972–

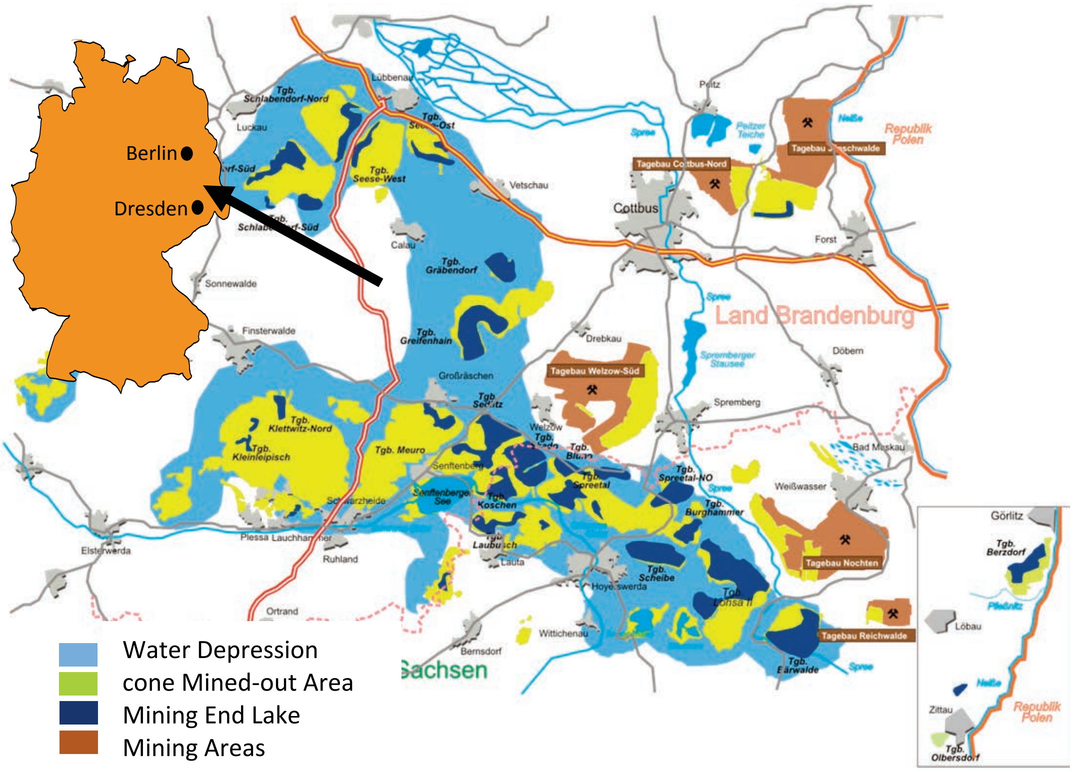

Fig. 1 *Impact on Groundwater in the Lausitz District due to Lignite Mining*

1975), followed by liming lake Koschen (2004–2005) and lake Burghammer (2009–2011).

In order to promote innovative techniques in water treatment of AMD, LMBV has launched a program called "Pilot- und Demo-Vorhaben". Within this program, new approaches derived from scientific research are tested full-scale and onsite. Based on basic research, application-oriented prototype testing proposals are evaluated according to feasibility, sustainability and economic results. After positive evaluation, these proposals are turned into testing projects either in dump areas, in the water bodies themselves or at the outflow of the lake. More than 80 proposals have been presented to and reviewed by LMBV over the past seven years out of which no more than twelve have been implemented. Few of these treatment techniques are ready to be implemented in remediation work.

The development of innovative liming technologies for in-lake treatment was focused on mobile treatment plants. Innovative neutralization technologies on mobile plants floating on the lake surface have been developed. Optimizing the liming process at Scheibe lake site, 380 mmol alkalinity were added in 16 weeks with effectiveness up to nearly 80 % on raw materials used. Further development work had been done in creating a hydrogen buffer by low suspension mixed in the lake waters. A specific technology developed underneath a special ship allows for high effectiveness during the distribution of the lime in the lake areas. Future development work is carried out on test implementation with hydro carbonate buffering with CO_2 gas injection. Further neutralization reagents are to be tested.

In-lake neutralization of Lake Bockwitz with soda ash

Lake Bockwitz consists of a number of smaller lakes within the former Leipzig mining area.

The Borna-Ost open pit was mined from 1961 to 1992. The open pit area is surrounded by dumps of tertiary und quartery materials to the south and west side, and by undisturbed terrain to the north and east. This area consists of glacial and fluvial sediments which are truncated by the bank slopes and laterally connected to the dump terrain. The flooding from 1993 to 2004 was realized by groundwater inflow originating from the tertiary fluvial aquifers. About 85 % of all inflow entered the lake's epilimnion laterally. The drainage area (3.1 km^2) is mainly comprised of bank slopes, of which about 30 % are uncovered (blank substrate and flutes), while 30 % are covered by scattered pioneer vegetation and grassland, 15 % by comprehensive grassland, and 25 % by young stands of trees (birch and pine). Surface runoffs and upstream interflow from the southern dump area enter Lake Bockwitz with low acidic load (Fig. 2).

From the beginning, the lake Bockwitz water was highly acidic (pH 2.7, Fe_{tot} 55 mg/L, Al_{tot} 19 mg/L) and did not meet the state authority criteria (pH >6, Fe_{tot} <3 mg/L, Al_{tot} <0.5 mg/L). Based on expert studies (Guderitz *et al.* 2003), in-lake treatment with soda ash was identified as the most reasonable treatment. Beginning in March 2004, light soda ash (99.4 % Na_2CO_3) was injected into the lake just below the surface through a floating pipeline located in the southern part of the lake. Within six years (2004–2011), a total of 17.2 kt of soda ash was supplied. Initial treatment shows a maximum efficiency of 62 %. It is estimated that 10 % of the added alkalinity neutralized the existing acid load from the surrounding overburden slopes and subsurface sources, 20 % were consumed by neutralization processes in the upper part of the lake sediment, and 5 % were consumed by losses through calcite precipitation. Considering the additional sinks of alkalinity, the soda treatment efficiency was between 90 and 95 %.

Even lake sediments have been identified by Boden- und Grundwasserlabor Dresden (BGD) as a source of net acidity through ion exchange processes, initially enhanced by soda treatments. However, the affected sediment depth will be limited (< 0.5 m), and residues of continued soda treatments may even provide a buffering capacity on the sediment surface.

Along with the soda additions, the acid inventory decreased and the sediment pH value increased from about pH 3 to 6.5. Later, the loss of acidity (*i.e.* H^+) in the sediment at this location was found to be in the same range as the increase of total sodium and calcium concentrations in the sediment bulk. Over 80 % of Na_2CO_3 in the sediment belonged to the exchangeable fraction. It can be assumed that about 10 % of the total Na+ supply with soda ash have been taken up by the sediment surface. The most consistent explanation for this phenomenon is cation exchange of Na+ and Ca^{2+} ions with protons absorbed into the sediment, thus enhancing the upward flux of acidity into the lake water (Fig. 3).

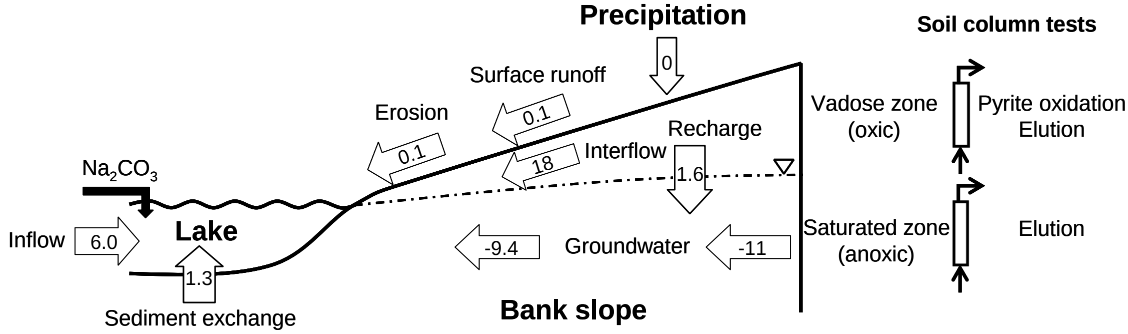

Fig. 2 *Major fluxes into lake Bockwitz, BNC and ANC fluxes in kmoL/d (Ulrich et al. 2012)*

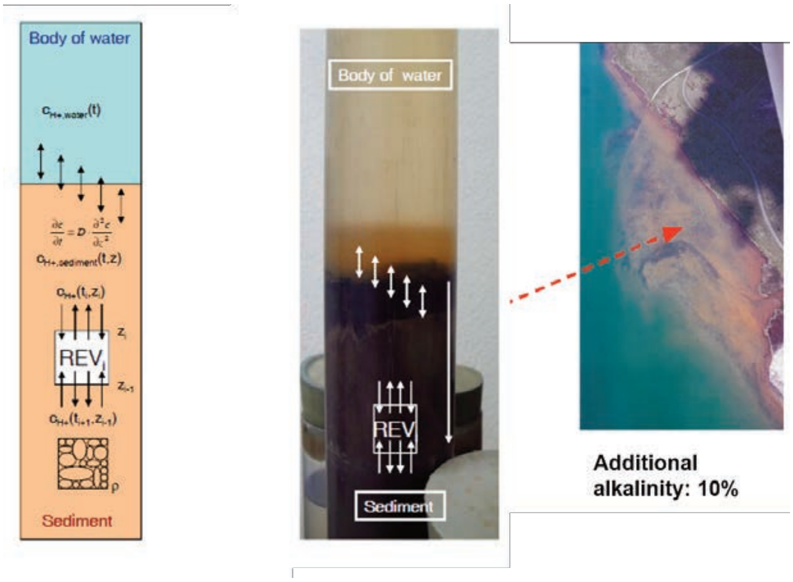

Fig. 3 *Exchange Process at lake sediments (Ulrich et al. 2012)*

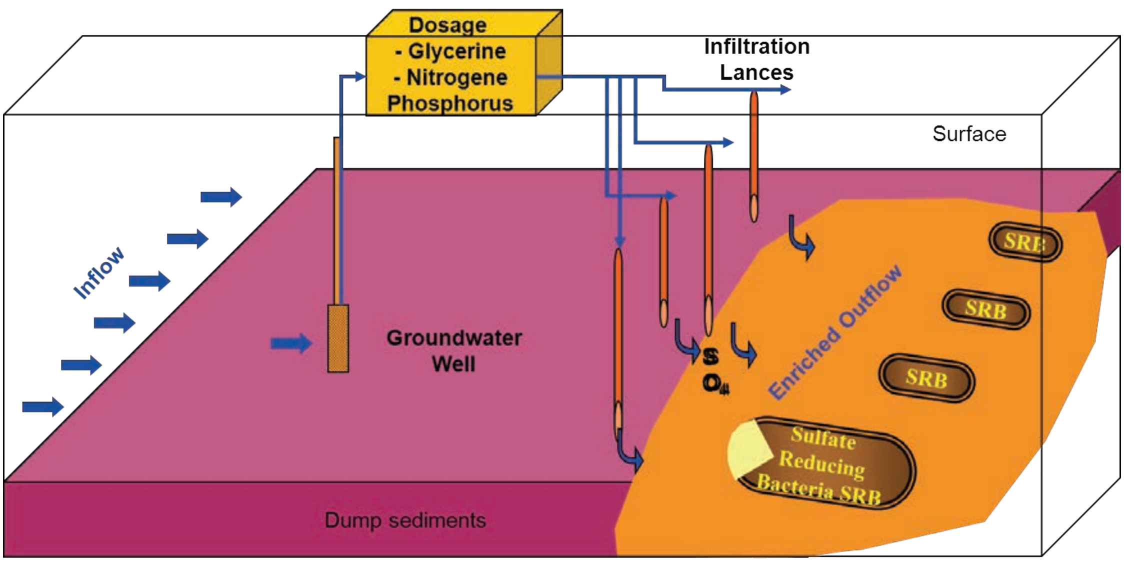

Fig. 4 In-situ *aquifer treatment plant for microbial sulfate reduction (Gast et al. 2010)*

Groundwater *in situ* aquifer treatment through microbial sulfate reduction

In order to reduce the acidic impact of groundwater inflow to the mining lakes, an innovative *in situ* aquifer treatment was developed.

Based on previous studies, the enhancement of the microbial sulfate reduction is considered to be the most promising method to improve groundwater quality in the upstream as well as in the downstream of lakes. Therefore, the Forschungsinstitut für Bergbaufolgelandschaft (FIB e.V.) and the Technische Universität Cottbus (BTU) designed an approach for *in situ* treatment of aquifers influenced by pyrite oxidation (Gast *et al.* 2010; Fig. 4). This approach aims to enhance the biochemical reduction of sulfate and iron in order to precipitate iron-sulfides in the aquifer. To enable the microbial-driven sulfate reduction, biodegradable organic nutrients are added to stipulate microbial catalyzed sulphate reduction. This was infiltrated by newly developed injection lances into the dump area. This led to the creation of a reactive zone in the aquifer that caused a significant reduction of sulfate, iron and potential acidity. The infiltrated glycerin was completely metabolized. This produced a carbon dioxide input to the water and generated an additional buffering capacity.

The quality of the groundwater is determined through infiltrated waters from Lake Partwitz as well as through the input of oxidized and acidic leachate from overlying sediments. The water that needs to be treated has a pH value of 4.9 – 5.1, concentrations of Fe^{2+} of about 230 – 320 mg/L and SO_4^{2-} concentrations of about 950 – 1150 mg/L.

The pilot plant was erected on "Skadodamm", an overburden dump between two mining end lakes. The hydraulic conductivities of this overburden are at about $k_f \approx 1{\cdot}10^{-5}$ m/s (light loamy sand), which are good conditions for *in situ* treatment.

In the middle of the pilot plant, a groundwater well hoists part of the water that passes through to the surface dosage station. At this stage, glycerin, nitrogen, and phosphorous fertilizer are added through an automatic dosage system. This mixture is directly infiltrated back into the aquifer by four injection lances (DSI-lances, Wils & Water GmbH, Germany) which are easy to install and highly economic. Infiltration takes place in depths of 15 m with rates between 0.8 to 1.8 m^3/h. The lances are charged individually with an automatic alternation every hour.

The dose of glycerin is based on the conditions mentioned above in order to allow 2.6 mmol/L in the infiltration water. In relation to the carbon input, nitrogen was added in a ratio of C/N = 25 and phosphorous in a ratio of C/P = 400. These ratios were derived from the estimated chemical structure of the microbial biomass. Within an operation period of 400 days, the groundwater in the downstream clearly shows an enhanced sulfate reduction (Fig. 5). Sulfate concentrations decreased by about 40 %; iron was removed completely. After a pause in the treatment of about 100 days, the sulphate and iron reduction immediately started after injection of nutrition. Meanwhile, the higher sulfide concentrations under special conditions allude to a lack of solute iron to be precipitated as FeS. This limitation requires a permanent monitoring and modulation of the input of organic matter. Otherwise, concentrations of solute sulfide may cause problems if outgassing of H_2S is conducted in a notable volume. In addition to the control of the organic matter input, an operation mode with pronounced breaks helps to mix iron-rich groundwater with the treated groundwater. The decomposition of glycerin is associated with an increase of TIC

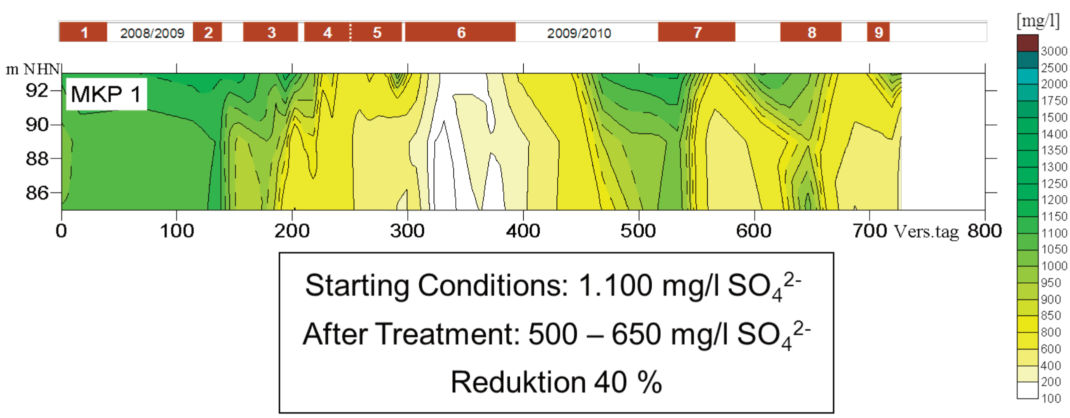

Fig. 5 *Sulfate reduction during treatment period*

that generates a considerable buffering capacity in the groundwater. This means that the groundwater was changed from an acidic quality to a significant buffering quality (Schöpke *et al.* 2013).

The operation of the aforementioned pilot plant was very successful. Furthermore, an adoption of this plant is projected to prevent groundwater inflow into nearby rivers banks.

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