A model-based study on the discharge of iron-rich groundwater into the Lusatian post-mining lake Lohsa, Germany

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Abstract As a result of the groundwater rise in the post-mining landscapes of the Lusatian lignite mining district, contaminated groundwater is entering the water courses. To prevent the groundwater contamination of the river Spree between the weir Ruhlmühle and the village Spreewitz, the preferred solution is to capture the iron-rich groundwater with a near river drainage system and discharge it into the nearby reservoir Lohsa II, a former pit lake.
The paper shows the examination of the hydrochemical and ecological consequences on the reservoir Lohsa II using a two-dimensional limnophysical model based on CE-QUAL-W2 4.0.

Key words pit lakes, ferrous und ferric iron, ochre sediments, limnophysical modelling

Introduction

As a result of the groundwater rise in parts of the Lusatian lignite mining district, contaminated groundwater is entering the watercourses. In many cases the groundwater is iron rich and potentially acidic. In the watercourse, the dissolved iron(II) oxidizes, precipitates as iron(III) hydroxide, deposits as an iron sediment on the river bed and inflicts thereby serious damage at the rivers ecology.

To reduce the iron burden of the rivers in the Lusatian lignite mining district a number of measures are examined, planned or already implemented by the Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV), the company responsible for the rehabilitation of the post mining landscape. To prevent the groundwater contamination of the river Spree between the weir Ruhlmühle and der village Spreewitz, the capture of the groundwater with a near river drainage system and the discharge of the captured groundwater into the nearby reservoir Lohsa II is preferred (Figure 1, Benthaus et al. 2015). In the reservoir, the groundwater can be treated with an existing ship-bound in-lake procedure. Therefore the costs for the water treatment can be reduced and the management of the iron sediment can be solved economically and ecologically. The iron sediment remains in the reservoir, which is covered by German water laws.

Basics

The reservoir Lohsa II originated between 1997 and 2013 in the former lignite open cast mine Lohsa and is divided into five deep basins: Nordostmarkscheide, Westmarkscheide, Drehpunkt Kolpen, Teilfeld 1/2 and Nordmarkscheide. The basins are connected by shallow areas. In the middle of the lake, an island has formed from the inner dump of the mine. On the highest water level of +116.4 m NHN, the lake has an area of about 10.8 km² and a sea volume of about 97.4 million m³. About 60.5 million m³ are available for water management (Figure 1).

Together with the reservoirs Dreiweibern and Burghammer, also former pit lakes, the reservoir Lohsa II forms the reservoir system Lohsa II. The reservoir system is located in the bypass of the river Spree. The inlet from the river Spree is located in the east and the outlet to the reservoir Burghammer is located in the north (Figure 1).

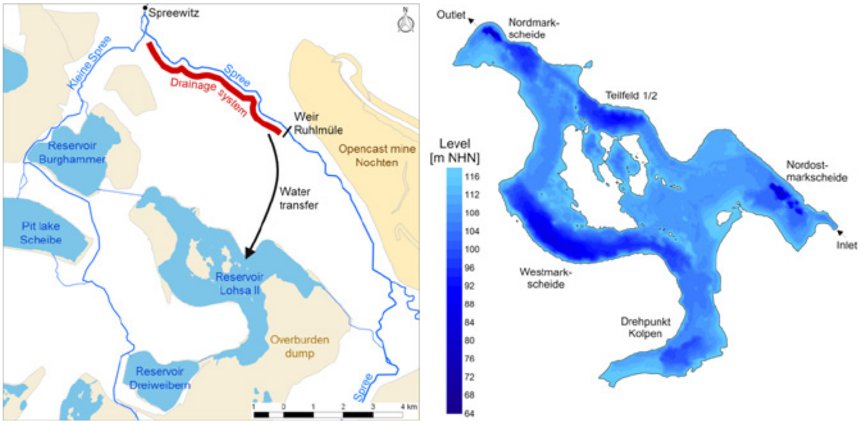

Figure 1*: Overview of the Lohsa II reservoir system (left) and the bathymetry of the pit lake Lohsa II (right)*

The reservoir Lohsa II is exposed to acidification. In December 2015 the reservoir was neutralized with calcium hydroxide by a ship-bound in-lake treatment (Geller et al. 2013). As a result, the pH-value could be raised to pH = 7 at present and the total iron concentration could be reduced to around 0.3 mg/l. Model-based predictions for the water quality in Lohsa II show that an annual follow-up treatment is necessary to prevent the reacidification of the reservoir.

The amount of groundwater to be captured with the drainage system at the river Spree was provisionally estimated with 0.4 m³/s (Figure 1). The groundwater is anaerobic and characterized by high iron concentrations up to 280 mg/L, a high acidity of approx. 10 mmol/l and a consistent temperature of around +12 °C.

Problem definition

It is expected that the discharge of the collected iron-rich groundwater into the reservoir Lohsa II will result in an increase of the iron concentration and a rapid reacidification. In order to minimize the hydrochemical and ecological consequences for the reservoir Lohsa II, the limnological, hydrochemical and procedural boundary conditions of the discharge have to be clarified. For this purpose, a model-based investigation was carried out on the following questions:

- What is the impact of the groundwater inflow on the reservoir's hydrochemistry, in particular the iron(II) and iron(III) hydroxide concentrations, as well as on the costs of the in-lake water treatment?

- How does the iron rich groundwater spread out in the reservoir and what external factors influence the spread?
- At which site and in what depth does the inflow of the groundwater have to take place in order to minimize adverse effects on the lake? Is the discharge into the shallow basin near the inlet (Nordostmarkscheide) more favourable than the discharge into the central and deep basin (Westrandschlauch)?
- Where in the reservoir does the iron(III) hydroxide deposits? What is the thickness of the iron sediment layer after a certain time? How much storage volume for the iron sediments is available in the reservoir and how long can the process be carried out?

Model selection

The spatial spread of the groundwater in the reservoir was investigated with the two-dimensional model CE-QUAL-W2 4.0, which was used before in similar investigations (Uhlmann et al. 2016). Model version 4.0 incorporates the oxidation of ferrous iron(II) to ferric iron(III) hydroxide and the sedimentation of ferric hydroxide as kinetic reactions of different complexity (Cole et al. 2016). The temperature dependence of the ferrous iron oxidation had to be supplemented in the source code of the model.

Model assembly

In CE-QUAL-W2, the reservoir Lohsa II is divided into segments whose positions and boundaries are derived from the bathymetry of the reservoir. The model reproduces the sequence of the deep basins and shallow areas. The main stream runs from the inlet through the deep western basin to the outlet and is represented by a single segment branch (Figure 1). The other basins as well as the "lagoon" in the island area are represented by separate branches. The reservoir was vertical discretized with 0.2 meter in the range of the water level fluctuations and with 0.5 meter in the remaining range.

Model calibration

The thermal stratification behaviour and the oxygen distribution were calibrated on measured temperature and oxygen profiles (Figure 2). For the calibration of the thermal stratification behaviour, the parameters for the wind and radiation influence as well as the ice cover of the lake were used. The oxygen distribution in the lake was calibrated via the oxygen consumption of the sediment. The parameters for the reaction kinetics of iron oxidation and iron sedimentation were derived from measurement data and laboratory tests.

Model application

Different sites and depth for the groundwater inflow were considered as variants (Table 1). The eastern shallow basin at the inlet from the Spree, and therefore the furthest from the outlet (Var.1), as well as the central and deepest basin (Var.2 to 4), are alternatives for the discharge of the iron rich groundwater. A basic variant without a groundwater inflow was used as basis for the evaluation. It is assumed in any case, that concurrently to the discharge of the iron-rich groundwater, the reservoir Lohsa II has to be neutralized. The acid-base state thus is determined by the carbonate balance.

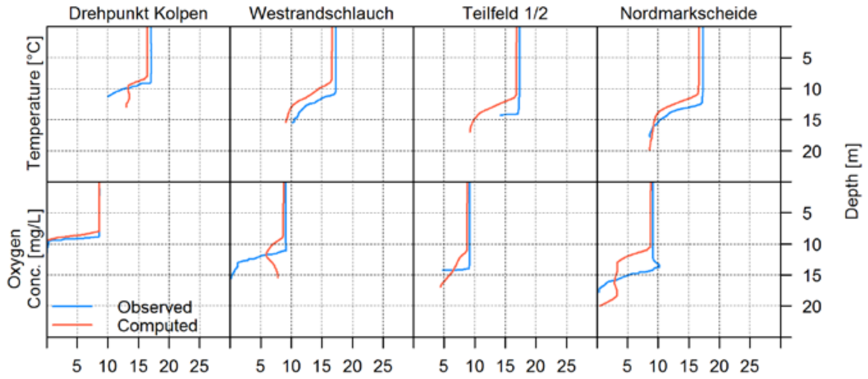

Figure 2*: Observed and computed temperature and oxygen profiles in the reservoir Lohsa II*

Table 1*: Investigated variants for the inflow of the iron rich groundwater into the reservoir Lohsa II*

Variant	Inflow site…	Inflow in depth…	Additive
0	---	---	
1	eastern basin	near surface (epilimnion)	calcium hydroxide
2	central basin	near surface (epilimnion)	calcium hydroxide
3	central basin	deep water (metalimnion)	calcium hydroxide
4	central basin	deep water (hypolimnion)	calcium hydroxide, oxygen

Model results

Thermal stratification behaviour and oxygen distribution

The thermal stratification behaviour of the lake is not significantly affected by the groundwater discharge in any variant. A stable dimictic layering behaviour is maintained in all investigated variants (Figure 3). At a near surface inflow (Var.1 and 2), the influence on the stratification behaviour is superimposed by atmospheric processes. An inflow in the deep (Var.3 and 4) leads only locally to a slight increase in the water temperature of the hypolimnion.

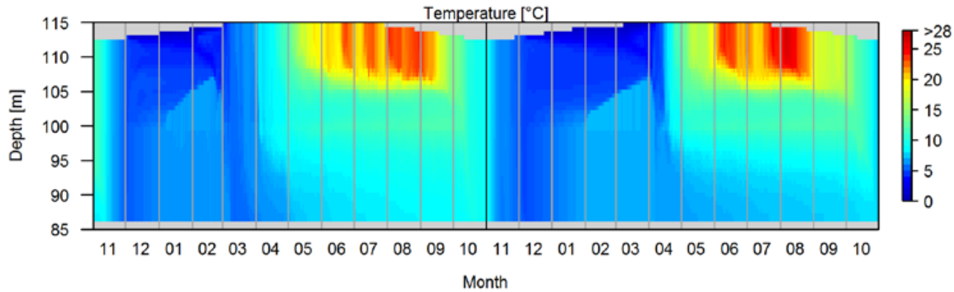

Figure 3*: Modelled temperature distribution in the central basin with a groundwater inflow in the metalimnion (Var. 3) in the model years 2002 and 2003*

At a near surface discharge of the groundwater (Var.1 and 2), there is always enough oxygen available for the oxidation of the ferrous iron. If the groundwater is discharged in the deep (Var.3 and 4), the available oxygen in the meta- and hypolimnion is completely consumed during the stagnation periods (Figure 4). This can be avoided with additional deep water aeration (Var.4).

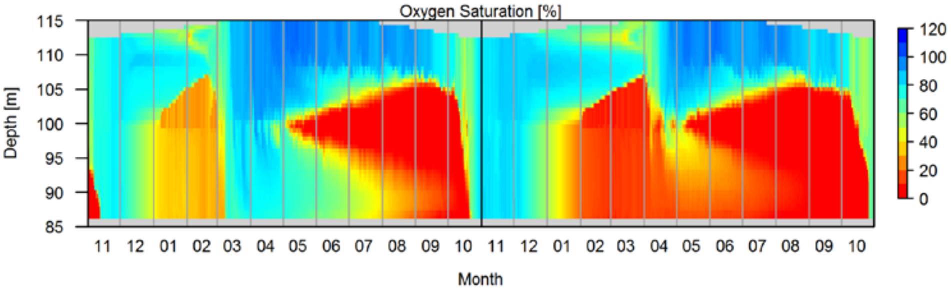

***Figure 4**: Modelled distribution of the oxygen saturation in the central basin with a groundwater inflow in the metalimnion (Var. 3) in the model years 2002 and 2003*

Spatial and temporal distribution patterns of the iron load in the reservoir

In the epilimnion, the iron(II) concentration does not rise above 1 mg/l in any variant. In case of a groundwater discharge in the deep (Var.3 and 4), the iron(II) concentration in the meta- and hypolimnion rises up to 20 mg/l during the summer stagnation period. The oxidation of the iron(II) enriched in the hypolimnion starts again with the autumn circulation period, when the hypolimnion is intermixed into the entire water body (mixolimnion).

At a groundwater inflow near the surface (Var.1 and 2), the iron(III) hydroxide concentration is increased during the summer stagnation period to 15 mg/l in the epilimnion and up to 20 mg/l in the hypolimnion of the deep basins. During the spring and autumn circulation, the iron(III) hydroxide concentration in the whole water body drops to around 10 mg/l.

If the groundwater is discharged in the meta- or hypolimnion (Var.3 and 4), a nearly permanent iron(III) hydroxide concentration of more than 20 mg/l is established there (Figure 5). When the hypolimnion is intermixed into the entire water body during the circulation periods (mixolimnion), the iron(III) hydroxide concentration at the surface of the reservoir spontaneously increases (Figure 5). Such events have already been observed empirically on several pit lakes in the area where the iron input originates from nearby mining dumps. During the summer and winter stagnation periods, the iron(III) hydroxide concentration in the epilimnion is invariably below 2 mg/l. In regard to the iron distribution in the reservoir, a groundwater discharge in the deep in combination with an additional aeration is advantageous.

Temporal iron load at the outlet of the reservoir

Of particular interest were the iron concentration and their temporal variability at the outlet of the reservoir Lohsa II. If the groundwater is discharged near the surface in the eastern basin (Var.1), the iron(III) hydroxide concentration at the outlet increases only for a few days over 2 mg/l. At a near-surface inflow in the central basin (Var.2), the iron(III) hydroxide concentration at the outlet is over 2 mg/l throughout the year because of the short distance between the inflow site and the outlet. In case of a groundwater inflow in the meta- or hypolimnion (Var.3 and 4), the iron(III) hydroxide concentration at the outlet increases only during the circulation periods above 2 mg/l.

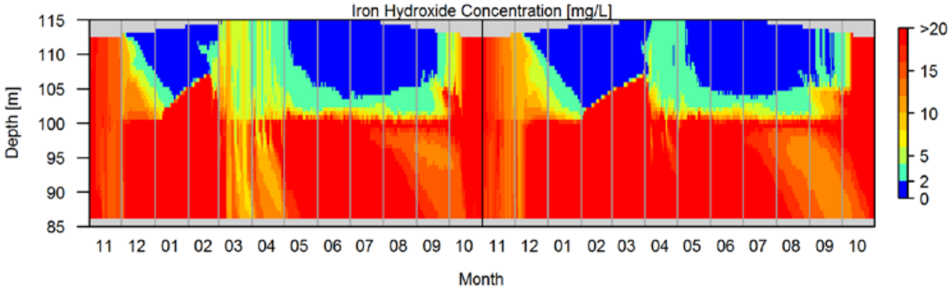

***Figure 5**: Modelled iron(III) hydroxide distribution in the central basin with a groundwater inflow in the metalimnion (Var. 3) in the model years 2002 and 2003*

Spatial distribution of iron sediments

Due to the precipitation of the iron(III) hydroxide, an iron-rich sediment deposit is formed. From experience, the sediment load can be assumed to have an iron content of 400,000 ppm and a dry residue of 5% by mass after medium-term consolidation. When the groundwater is discharged near the surface (Var.1 and 2), the iron(III) hydroxide is distributed over the whole lake, so that the iron rich sediments are deposited nearly everywhere in the reservoir. After 20 years, a sediment thickness of around 1 meter is expected almost in the entire lake (Figure 6, left). When the groundwater is discharged in the meta- or hypolimnion of the deep central basin (Var.3 and 4), the spreading of the iron(III) hydroxide is strongly restricted and the iron sediments are mostly deposited in the deep water areas. After 20 years a sediment thickness of approx. 2.2 meter is expected in the central basin. In the rest of the reservoir the sediment thickness is significantly smaller (Figure 6, right). The extrapolation of the calculations shows that the Lohsa II reservoir can be used for at least 50 years for the discharge of the iron-rich groundwater without losing its basic limnological properties as a dimictic lake.

Conclusions

The model results show that the discharge of the iron-rich groundwater into the pit lake Lohsa II is a technically feasible option for the treatment of the groundwater and the storage of the resulting iron sediments. However, due to the hydrochemical properties and the considerable amount of the groundwater inflow, a supplementary water treatment (neutralization, aeration of the hypolimnion) is necessary.

A groundwater inflow near the surface offers the advantage of a sufficient oxygen supply for the iron oxidation. It is however disadvantageous that the iron(III) hydroxide produced during the oxidation spreads over the entire surface of the lake and also sediments in the ecologically important littoral zones.

When the groundwater is discharged into the reservoirs meta- or hypolimnion, the spread of the iron(III) hydroxide is strongly restricted. However, the limited oxygen supply in the deep water is consumed entirely by the ferrous iron oxidation. This leads to a corresponding oxygen deficiency in the stagnation period and subsequently to an increase of the fish-toxic iron(II) concentration. This disadvantage can be remedied by an aeration of the deep water. The selection of the inflow site is determined by the available storage volume for the iron sediments. The storage volume in the central sub-basin is much larger than in the other basins of the reservoir. The disadvantage of temporarily increased iron(III) hydroxide concentrations at the outlet of the reservoir must be taken into account.

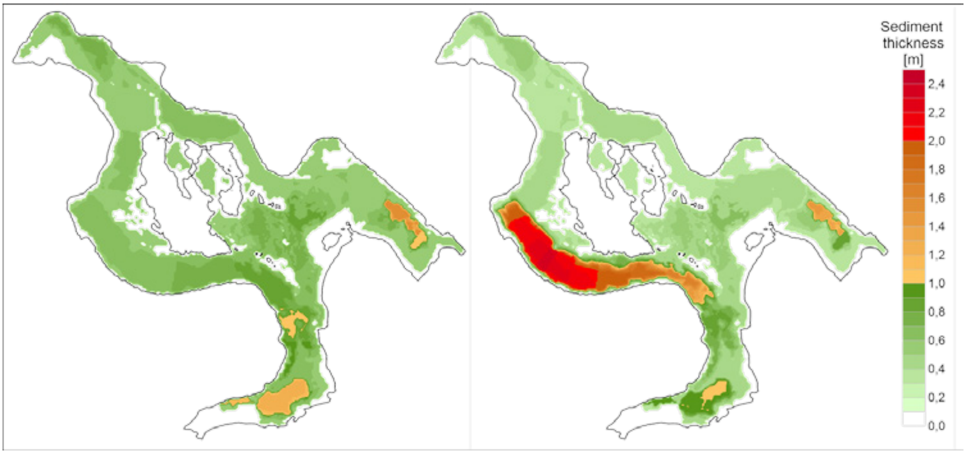

Figure 6*: Projected thickness of the iron sediments in the reservoir Lohsa II after 20 years with a groundwater inflow near the surface (Var. 2, left) and in the metalimnion (Var. 3, right) of the central basin*

Acknowledgements

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