Groundwater Surface Water Interaction of a Post Lignite Mining Lake in Germany and its Relevance for the Local Water Management

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Abstract

Lake Baerwalde is a lake that resulted from open pit lignite mining in the East German mining district. It has been filling with surface waters since 1997. Its current volume is approximately 100 $*10^6$ m^3 which is about 60% of its final volume. The pH of the lake water has remained at a level of around pH 3 since the beginning of the flooding. Nevertheless, acidity has dropped significantly from over 10 mmol/L to well below 2 mmol/L. After reaching its final level, the lake will discharge into the river Spree. Downstream of the mining district, bank filtrate from the river Spree is used for the water supply of the city of Berlin. The evolution of the lake water quality strongly depends on the water balance of the lake. Based on monitoring results of the flooding process, the net groundwater discharge from the lake is calculated. The fluxes are calculated for a period of 5 years on a monthly basis. High infiltration rates into groundwater in combination with low exfiltration rates from groundwater lead to favorable conditions for the development of lake water quality. Existing predictions of lake water quality depend on this factor (i.e. the water balance) rather than on the degree of simplification applied to the surface water model. The response of the lake water level according to periods of high and low surface water input was used to calibrate the groundwater flow model which is based on a detailed 3-D geological model. A large set of borehole data from the mining exploration was used to set up a 10 layer model of the geological structure to store hydraulic as well as geochemical data.

Introduction

Lake Bärwalde is one of about 12 post mining lakes that are currently being established in the catchment of the river Spree. These lakes are interconnected with the river Spree or its tributaries to accelerate their filling, to improve their water quality and to control their water levels.

After Lake Bärwalde has reached its final lake level it will be the first (located most upstream) post mining lake in the course of the river Spree to contribute water to the river. This is planned to occur in 2005. The lake will serve as a reservoir to buffer high and low water levels of the river. This assigns Lake Bärwalde a high importance in the ongoing flooding process of the lakes located downstream. The availability of sufficient surface water is a major problem in the management of the flooding process. Water quality of these lakes is often dependent on the speed of filling, as high amounts of dissolved ions are leached from the banks of the lakes. Main pollutants are dissolved metals that release acidity and dissolved sulfate. The storage volume of Lake Bärwalde will be about 24 $*10^6$ m^3. A requirement for the operation of the reservoir is an acceptable water quality.

Due to the hydrological and geological conditions in this mining district, a strong interaction between groundwater and these lakes exists. The pre mining groundwater levels were very close to the ground surface. The hydraulic conductivity of the stratigraphic units covering the tertiary lignite seams is generally very high. The lakes are deep (up to 50 m) and large in extent (several square kilometers) cutting through a mainly vertical layered system. Acid mine drainage is a common problem in the area. Main sources of acidification are the artificial aquifers that consist of overburden material. Pollutants are released into the ground water and transported to the lakes or are directly leached from the banks of the lakes and streams.

Water Budget of Lake Bärwalde

The flooding of Lake Bärwalde is documented by the government owned Lausitz Mining Administration Company (LMBV) that is in charge of the rehabilitation of the post mining landscape. Lake and groundwater monitoring data were supplied to enable a research project that was conducted in the years 1999 to 2003 (DGFZ 2003). Figure 1 shows the input of surface water into the lake and the rise of the water level. During the period of 5 years from January 1998 to December 2002 a river water volume of 161

$*10^6$ m^3 was put into the lake. That created a rise of the lake water level from 98.8 m above sea level (a.s.l.) to 119.9 m a.s.l..

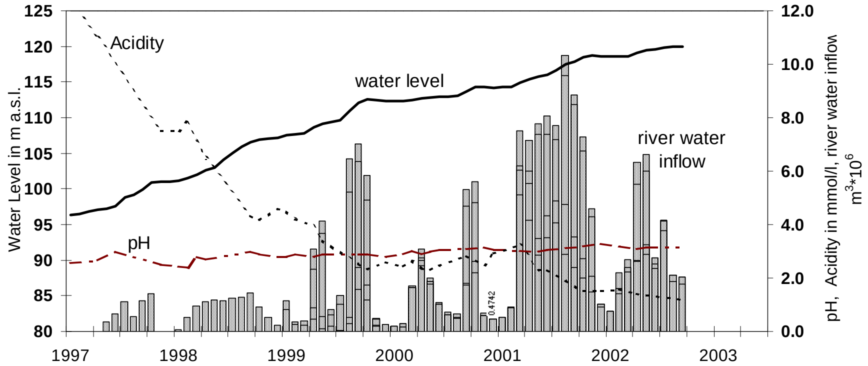

Fig. 1. Water level, pH, acidity and surface water input for Lake Bärwalde

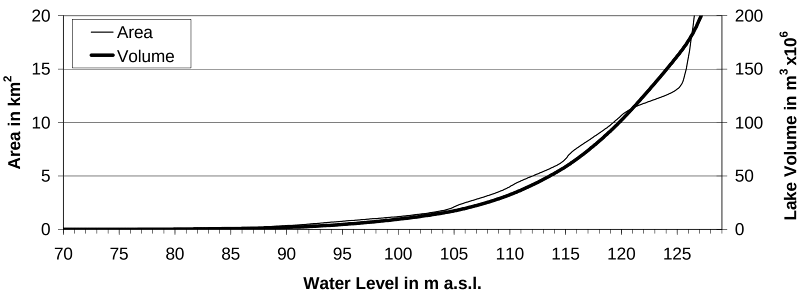

Fig. 2. Relation between lake level and lake volume/surface area

In the same time, pH remained more or less constant at about 3 whereas acidity dropped significantly from 9.7 mmol/L to 1.5 mmol/L. Figure 2 shows the functional relation between water level and lake volume/surface area (h-v-function) as calculated from the digital elevation data.

An increase in the lake volume of 92.7 $*10^6$ m^3 water for the 5 years period is derived from the h-v-function (Fig 2). The remaining 68.37 $*10^6$ m^3 of water have not contributed to the increase in volume. To discuss the fate of this water, the components of the water balance will be analyzed. These are:

- surface water inflow
- surface water outflow
- groundwater inflow
- groundwater outflow

- the difference between precipitation and evaporation
- the change in volume of the lake

surface water inflow. This part of the water balance can easily be taken from the monitoring data (Fig 1). As mentioned above, the value is $161*10^6$ m^3 for the period of 5 years.

surface water outflow. Until the lake has reached a level of 125 m a.s.l. no surface water outflow can occur. It is zero for the period from 1999 to 2002.

groundwater inflow. The time dependant magnitude of the groundwater inflow was calculated in two independent groundwater modeling studies. Both calculations match fairly well, yielding an inflow of about 0.1 to 0.2 m^3/s. For the period of 5 years from DGFZ (2003) the value of 32.7 $*10^6$ m^3 is used.

groundwater outflow. This part of the water budget is treated as the unknown for which the budget is to be solved.

The difference between precipitation and evaporation. The gain or loss from open water bodies due to the climatic conditions is dependant on the water depth and shows a seasonal variation. For the purpose of comparing the single parts of the budget a mean annual precipitation of 628 mm and an evaporation of 701 mm was extracted from the seasonal data. For the period of 5 years, this sums up to a net loss of 2.3 $*10^6$ m^3

The change in volume of the lake. This part of the water balance can again easily be extracted from the monitoring data (Fig 2). The error that is created by small variations in the water level due to wind is large for small time steps. For the period of 5 years this error is small. The change in volume is 92.7 $*10^6$ m^3.

From these values the groundwater outflow may be calculated to be 161-0+32.7-2.3-92.7 = 98.7 $*10^6$ m^3 for the period of 5 years. This corresponds to an outflow rate of 0.62 m^3/s .
The groundwater budget is calculated by outflow - inflow (98.7 - 32.7 $*10^6$ m^3) to be 66 $*10^6$ m^3 for the period of 5 years, or 13.2 $*10^6$ m^3/year. The groundwater cone of depression that had been created by mining was decreased with this water. Figure 3 depicts the discussed parts of the water balance.

The outflow from the lake into groundwater is replenished by river water. Subsequently, more alkalinity can be imported into the lake by flooding in the remaining time until the final lake level is reached and outflow is discharged in to the river.

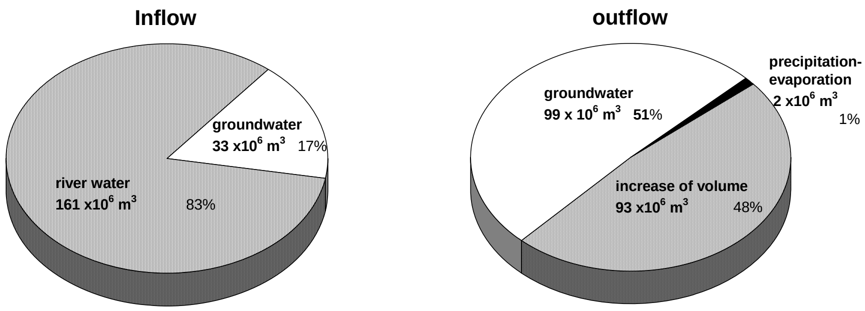

Fig. 3. Elements of the water budget for lake Bärwalde summing up the period of 5 years from 1998 to 2002

Lake Water Quality

The water quality of Lake Bärwalde is characterized by acidification and high sulfide concentrations. The pH of the water was 3.2 in March 2003. A change in the acid content of the water is not expected to result in a change in pH until the acidity (titration acidity to the end point of 4.3) is approaching zero. The fact that acidity has dropped significantly can be seen in the monitoring data. In the beginning of the flooding, high surface water input caused the acidity in the lake to drop. Between April 2000 and October 2001 reduced surface water input caused the acidity of the lake to stagnate. River water with a mean alkalinity of 1.2 mmol/L was imported with a mean flux of 0.89 m^3/s.

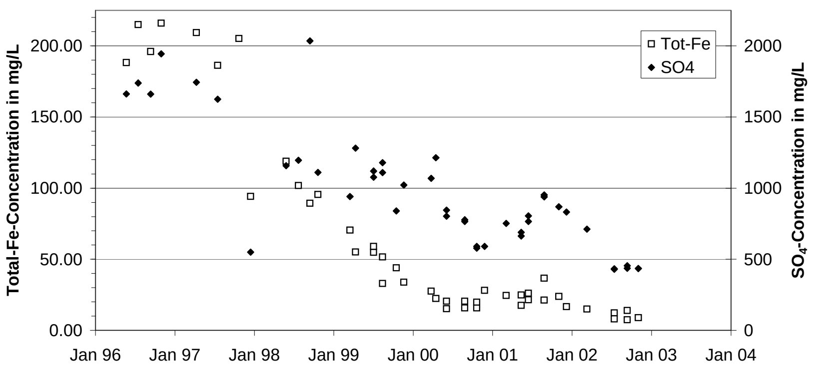

Fig. 4. Development of total iron and sulfate concentrations in Lake Bärwalde

From this stagnation, the acid flux that is received by the lake due to bank erosion/leaching can be estimated. This estimation from the monitoring data is an important method of checking modeling results for plausibility. Figure 4 shows the change of total iron and sulfate concentrations in the lake over time.

Total iron concentrations can be well correlated with acidity shown in Fig. 1. This is in good accordance with the fact that iron hydrolysis and precipitation is the main reason for acidification in the lake. Sulfate concentrations decreased over the monitoring period as a result of the surface water inflow, with mean sulfate concentrations of around 100 mg/L. Concentrations of main dissolved ions in the lake water are presented in Table 1.

Table 1. Representative concentrations of dissolved ions in lake water, inflowing groundwater and river water in 2001. Acidity and alkalinity is titrated to endpoint pH 4.3

		Lake Bäwalde	river water	ground water
	units			
pH	-	2.9	7.3	6.2
Acidity	mmol/L	2.4		
Alkalinity	mmol/L		1.2	
TIC	mg/L	1.4	10	30
Na	mg/L	15.1	10	15
K	mg/L	5.0	6	14
Ca	mg/L	123	55	300
Mg	mg/L	29.5	8	100
Fe	mg/L	25	0.3	160
Al	mg/L	10.7	0.2	0.6
SO4	mg/L	486	90	1200
Cl	mg/L	27	45	70

Water Quality Prediction

At the end of the rehabilitation of the former mine, a lake that can be used as a reservoir will be established. To discharge water into a tributary of the river Spree the water quality must meet a standard set by authorities. The standard is defined by a pH-value between 6 and 9and maximum concentrations of total iron (3.0 mg/L), dissolved iron (1.0 mg/L), sulfate (250-500 mg/L, depending on the receiving surface water), ammonia (1.5 mg/L), zinc (1.0 mg/L) and copper (0.04 mg/L). A failure to meet these goals by the time the lake has been filled to its final level means that it cannot be operated as a reservoir and that the discharging water must be treated. If the reservoir cannot be operated, the flooding of other post mining lakes is strongly affected. The management of water distribution is dependent on a number of minimum water level and minimum water flux conditions for certain locations along the rivers, creeks and channels in the area. Predictions of the water quality of post mining lakes in the east Saxon area have been reported by Uhlmann (1995), Werner et. al 2001, Müller et.al (2002) and Müller (2004). They are regarded as a basic tool in the decision making of the water management. Similar methods were used in all studies following several steps:

- the estimation of the water balance of a lake for future hydraulic conditions
- assigning mass fluxes to the water fluxes based on representative sampling of the hydraulic fluxes
- the estimation of mass fluxes driven by the leaching of erosion transported soil material into the lakes
- simulating reactions in the surface waters. The main processes governing the chemical state of the water are the exchange of gases (O_2 and CO_2) between the atmosphere and the surface water and the oxidation, hydrolysis and precipitation of iron and aluminum.

Only one author (Müller 2003) has reported the application of a multi-dimensional model to simulate the hydrodynamics and reactions within a lake embedded in the prediction model. The other authors used 0-dimensional mixing cell models for the reactions in the lake.

Surface Water models

The application of surface water models in the context of predicting the lake water quality of east Saxon post mining lakes is focussed on the simulation of chemical reactions. From the balance of the water and mass fluxes that flow in and out of the body of surface water, the total concentration of dissolved ions is known. As mentioned above, the main reactions are the heterogeneous reactions between the constituents of the water, the atmospheric gases and the (possible) solids that might precipitate. The application of 0-dimensional models on large lakes neglects the fact that these lakes may be stratified and thus may consist of two compartments with geochemically very different conditions. It is shown in Fig. 5, that in the case of Lake Bärwalde a simulation using MODGLUE (Müller 2004) did not reveal significantly different water qualities for the two compartments (the epilimnion and the hypolimnion of the lake). A 0-dimensional model that is able to reflect mean redox conditions in a lake needs to rely on effective values for the partial pressures of the gases. These are problematic to predict. On the other hand, in the spatial distributed simulation the process of gas transfer at the surface and the hydrodynamic transport can be simulated based on the actual process.

Another important difference between the different modeling studies is the definition of the possible solids that are allowed for precipitation. This includes their stochiometric definition and the thermodynamic data to calculate saturation. The minerals ferrihydrite and schwertmannite, for example, exhibit different ion compositions and solubilities. The practical differences for a prediction result however appeared to be small when different modeling results for Lake Bärwalde were compared. The stoichiometric acidity release that is created by the precipitation of both minerals differs by less than 10%.

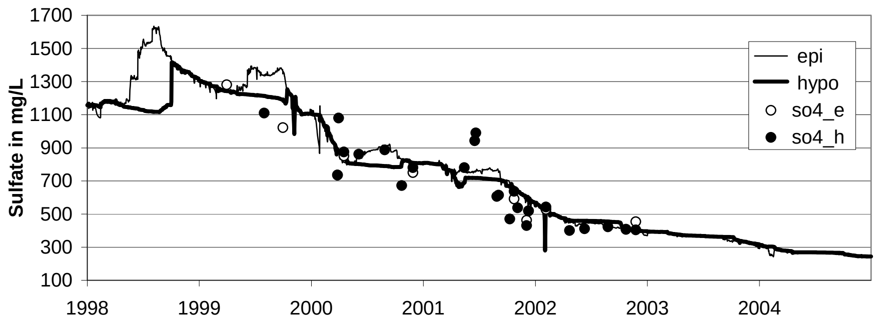

Fig. 5. Water quality simulation for Lake Bärwalde using the MODGLUE Model (Müller 2004). Circles indicate measurements (non filled- Epilimnion, filled - hypolimnion). Lines indicate simulated data.

In comparing the results of a simple 0-dimensional mixing cell model and the advanced MODGLUE model, additional conceptional differences must be discussed. MODGLUE includes a modified version of CE-QUAL-W2 (Cole and Buchak 1995) for hydrodynamics and algal growth. The 0-dimensional model does not include biological processes. Nevertheless, it is stated that for the investigated Lake Bärwalde case both models give similar results, provided they are based on identical mass fluxes across the boundary groundwater-lake and identical mass fluxes due to erosion. Biological primary production in the MODGLUE model Bärwalde was small as it was limited by the availability of carbon due to low pH-values. Inorganic mass fluxes driven by the import and precipitation of iron dominated the system.

Ground water models

There are no conceptual differences between the two existing groundwater models of the Lake Bärwalde area. Boundary conditions are almost identical and general agreement prevails about the representative hydraulic conductivities for the single aquifers. Nevertheless, the results for the future magnitude of the groundwater discharge differed significantly. This caused the water quality predictions to differ as well. As the water management planning demanded unambiguous data for decision making, the reasons for the differing results of both models were closely investigated. A new calibration was performed using the latest monitoring data and taking into account the results presented in the section "water balance" concerning groundwater discharge. The main difference in the models was the vertical resolution. It turned out that the complex hydrogeology in the main discharge area of the lake (Fig. 6) was able to produce very high groundwater fluxes.

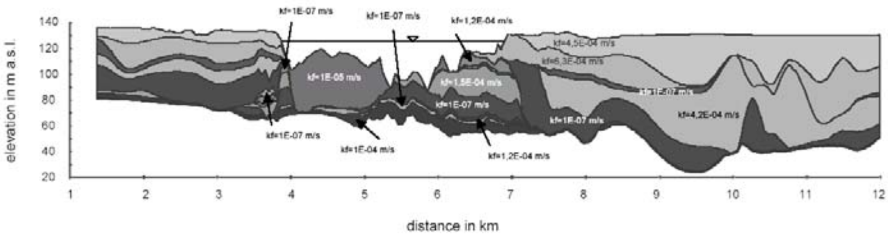

Fig.6. Hydrogeological cross section showing the underground structures in the area where groundwater discharge from Lake Bärwalde appears

Conclusion

Water management in the east Saxon post mining area is a complex task of distributing the available river water among all users. The filling of mining lakes with surface water is a key strategy to minimize ecological impact and economic effort. In the planning of future actions, predictive modeling is an important tool for the management tasks. The value of this tool is determined by the precision of its predictions. In the presented case, the prediction of the water quality of Lake Bärwalde strongly depended on the predicted discharge from the lake into the groundwater. The readiness to improve groundwater models in cases where models already exist is often low. This is especially true if existing models have proven to be reliant in earlier cases, like the design of dewatering schemes. For the modeling of groundwater rise in areas like the east Saxon mining area that have been dewatered over a long period,, only sparse data is available for use in calibrating groundwater flow within the uppermost parts of the aquifers. This creates the need for a high vertical resolution of the hydrogeologic model and transfer of this information into the numeric model.

Acknowledgement

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