PREDICTED AND OBSERVED WATER QUALITY DATA FROM THE COAL MINE PIT LAKE BÄRWALDE, LAUSTZ, GERMANY[1]

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Abstract. German Pit Lake Bärwalde has been flooded since 1997 with surface water. Its current volume is $100 \cdot 10^6$ m^3 with a maximum depth of 50 m. Waste rock consists of porous media, with a medium sulfide-S content of 0.3 wt%. The dimictic lake is acidic. Comparison of the monitoring data and earlier predicted model results give a good insight into the governing processes at the site. Modeling of the lake's internal processes with MODGLUE shows that the water quality of Lake Bärwalde is dominated by the import and export of acidity and alkalinity. Existing models were partly modified and coupled. Internal production of alkalinity due to primary production was included based on the water quality algorithms of the model CE-QUAL-W2. This model was modified to handle changing pH and alkalinity conditions by including carbon in the calculation of the production rates in the same way the nutrients were handled. For low pH conditions carbon limitation can be modeled. The hydrodynamic transport capabilities of CE-QUAL-W2 were used unmodified to calculate the 2-D spatial distribution of constituents within the lake. Changes in pH and the oxidation and precipitation of metals were calculated using the model PHREEQC.

The evolution of the water quality in the lake can be explained by the water fluxes, the reactions in the lake and the erosion and leaching of the bank material. High ground water outflow from the lake is favorable with respect to an effective lake flushing.

Additional Key Words: Pit lake models, surface water flooding

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Introduction

The Lausitz (Lusatia) post mining landscape in Germany is located in the eastern part of the country south of the capital Berlin and close to the border with Poland. The government owned Lausitz Mining Administration Company (LMBV) is in charge of the rehabilitation of the post mining landscape. The goal of the rehabilitation is to restore the water budget deficits in ground and surface water and to achieve an acceptable water quality. Around 40 pit lakes are partly water filled. The total pit lake volume in this area will be around $2.5 \cdot 10^9$ m^3 in its final state. Currently about half of that volume has been filled mainly using surface water. Surface water flooding and lake flushing are the major instruments to accelerate the rehabilitation and to establish a good water quality.

Lake Bärwalde is located in the River Spree catchment area (Fig. 1). It has been filled with surface waters since 1997. Its current volume is approximately $100 \cdot 10^6$ m^3 which is about 60% of its final volume.

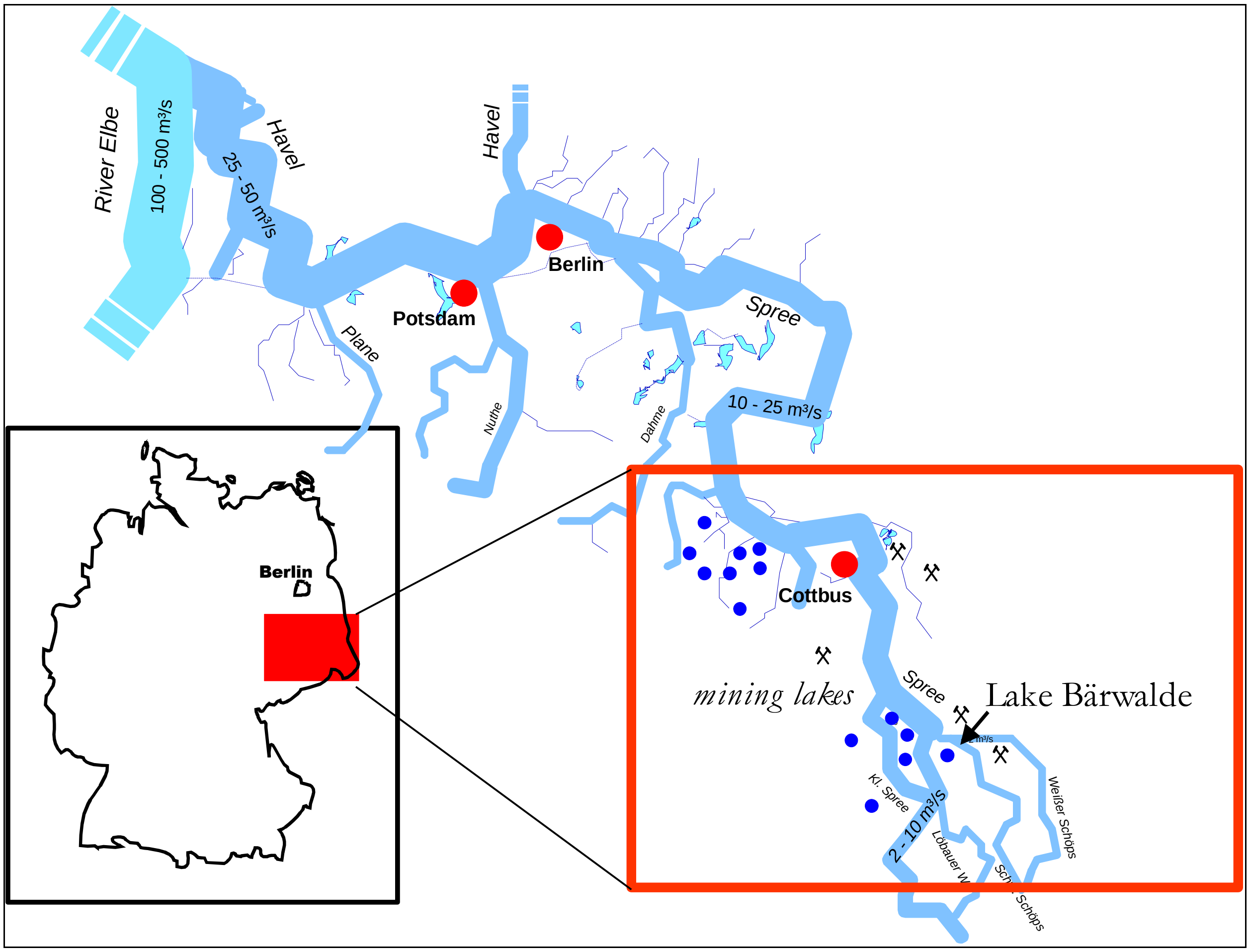

Figure 1. Lake Bärwalde in the River Spree watershed. Blue dots indicate pit lakes.

The pH of the lake water has remained at a level of around pH 3 since the beginning of the flooding. 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. The lake will serve as a reservoir to buffer high and low water levels of the river. The storage volume will be about $24 \cdot 10^6$ m^3.

The question whether the lake will turn neutral before it reaches its final water level or not, is crucial, because regulations do not allow acidic water to be discharged into public rivers. The objective of the paper is to aid decision making for long time planing with predictive modeling. The planning and implementation of any action to treat the effluent water or the whole lake demands a certain time span to be able to react adequately. On the other hand this action might not be necessary if the lake is neutralized during the flooding.

The presented method cannot be used at another pit lake without considering the local characteristics of the climatic, hydrologic, or geologic system. The worldwide variety of examples for pit lakes creates the need for specific and often differing solutions of how to describe and quantify their governing processes. Cornerstones describing the local characteristics of the Lausitz post mining area are:

- High hydraulic conductivities in sand/gravel aquifers;
- Absence of carbonates (apart from Quaternary tills);
- Sulfides in tertiary sediments in the order of 0 - 2 wt%;
- Pits remaining from strip mines (lignite seam approximately 40-60 m below surface);
- All lakes are connected to rivers with inflow and outflow and most will discharge at final lake levels into rivers;
- Flooding with river water is the favored strategy.

Site Characterization

The regional geology is characterized by tertiary sediments that were partly eroded and disturbed by Pleistocene glaciation. Scandinavian glaciers repeatedly covered this area. Open pit mining was conducted to mine the Miocene lignite (brown coal) from 1971 to 1992. A compilation of available geological data and its utilization for remediation purposes was documented by Graupner et al. (2005). Based on over 3000 borehole datasets from lignite exploration a set of 3-D digital geological models representing the pre and post mining states was set up by these authors. The model area was about 12 km x 10 km. Sulfide contents within the 15 stratigraphic units that had been sampled during the mining exploration were assigned to the model. A representation of that model is shown in Fig. 2.

The sulfide contents in the tertiary deposits range from 0.1 to 0.7 weight percent. Quaternary sediments contain sulfide contents from less than 0.01 to 0.3 weight percent. For the mining dump, the original sulfide content could be calculated from the geometric mixing of the overburden within vertically averaged blocks of 100 x 100 m. For an average turnover rate from sulfide to SO_4^{-2} of 7% for the whole dump body, the resulting total oxidized mass of S was calculated to be about 0.18 million metric tons of pyrite S for this site. Graupner et al. (2005) estimated an average SO_4^{-2} concentration within the dump of 9 mol/m^3. This SO_4^{-2} mass is believed to be mobilizable by the rising ground water. Measured concentrations of SO_4^{-2} and Fe^{+2} iron in the groundwater flowing through this dump are 4.4 mmol SO_4/L and 4 mmol Fe/L.

If the calculation of the source amounts is in the correct order of magnitude, the calculated source could produce the measured concentrations in the groundwater discharge for many decades, depending on the length of the flow path that leaches the source.

All predictions of the further development of Lake Bärwalde use the measured concentrations for the single water fluxes that contribute to the water balance of the lake. This seems to be well justified for the background concentrations in the anthropogenic unaffected water bodies. Based on the above discussed calculations, this seems to be as well justified for the effluent ground waters from the mining dump, provided that the time frame of the predictions are focused on the flooding period to be managed today.

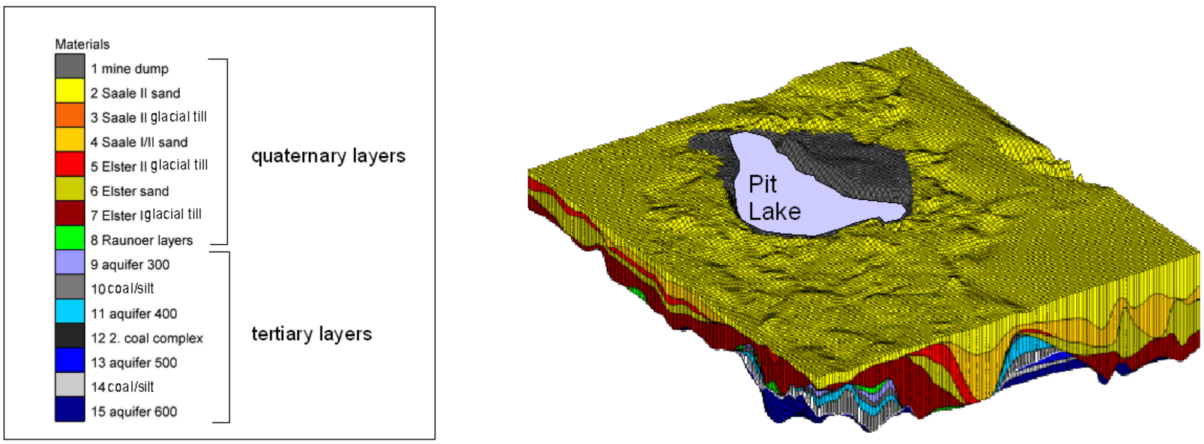

Figure 2. Geologic model of the vicinity of pit Lake Bärwalde. Main ground water flow direction is from the left (south) to the right (north).

The morphometry of the pit lake is shown in Fig. 3. The arrows indicate surface water and ground water in- and outflow areas. The future water outlet from the lake is located at the northern shore. The maximum depth of the lake is about 50 m. The deep parts of the lake originate from the former strip mine geometry. The shallow parts that are just covered by the lake level of 121 m above sea level are a possible source of acidity caused by sediment leaching. The ground water flow to the north of the lake is caused by the groundwater cone of depression of an active lignite mine located some 4 km north of the lake.

Flooding History and Water Balance

The flooding of Lake Bärwalde is documented by the 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 from 1999 to 2003 (DGFZ, 2003). Figure 4 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 $x \cdot 10^6$ m^3 was added to the lake. That created a rise of the lake water level from 98.8 m a.s.l. to 119.9 m a.s.l. At 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. The given values for acidity represent the base consumption in a titration with an endpoint pH of 4.3. The units are mmol charge /L.

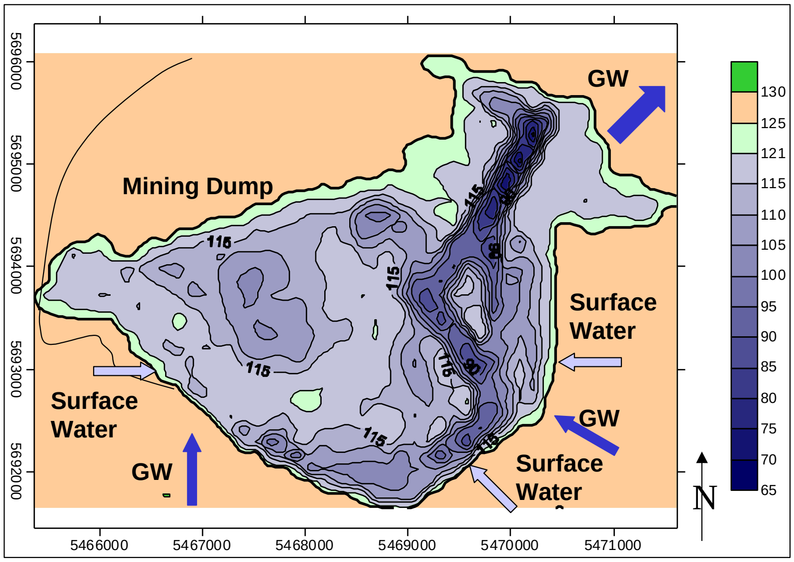

Figure 3. Morphometry and recharging water fluxes of Lake Bärwalde. "GW" is indicating ground water inflow. The heavy black line shows the future shoreline. Units for the color bar are elevations in meters above sea level (a.s.l.). The blue colors depict water for a lake level of 121 m a.s.l. The x and y axis show the latitude and longitude of the site.

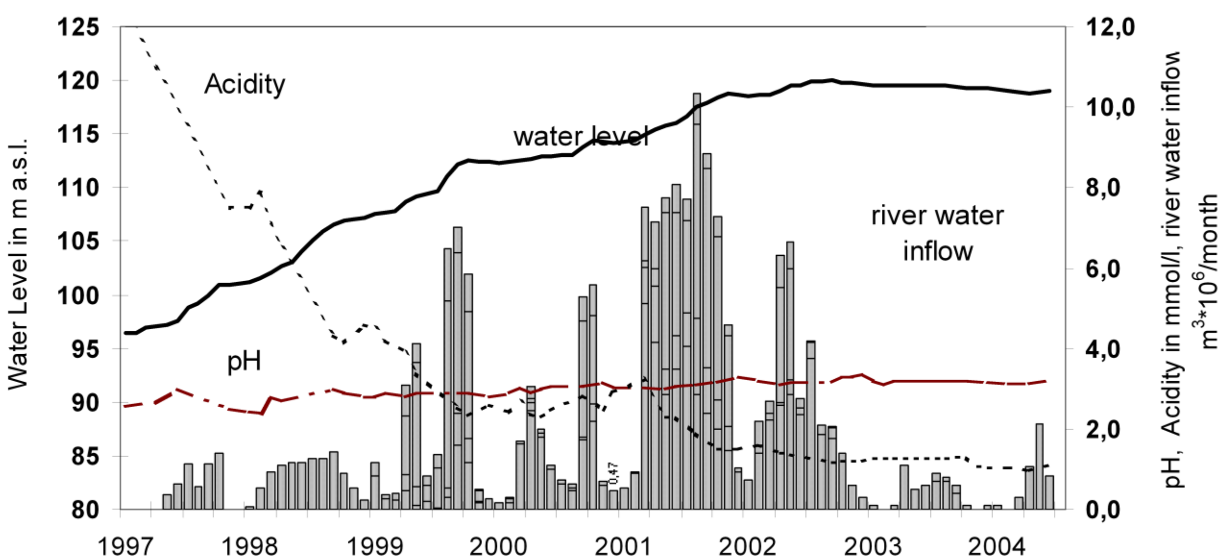

Figure 4. Water level, pH, acidity and surface water input for Lake Bärwalde.

During the years 2003 and 2004 ground water outflow and evaporation exceeded the sum of water inflows and the water level dropped by almost a meter. The quantity of ground water inflow into the lake was calculated (DGFZ, 2003) using the flow model PCGEOFIM (Sames and

Boy, 1999) and was assured by independent modeling performed by the owner of the lake (unpublished data). Using the relation between water level and volume of the lake and available precipitation and evaporation data the water balance of the lake can be calculated (Fig. 5, from Werner et al. 2004). Surface water inflow was taken from the monitoring data (Fig. 4). No surface water outflow occurred. Ground water inflow is a rather small amount in the water balance of Lake Bärwalde. Approximately half of the water the lake received during the evaluated time period increased its volume; the other half was infiltration into ground water. This is an important fact for water quality issues.

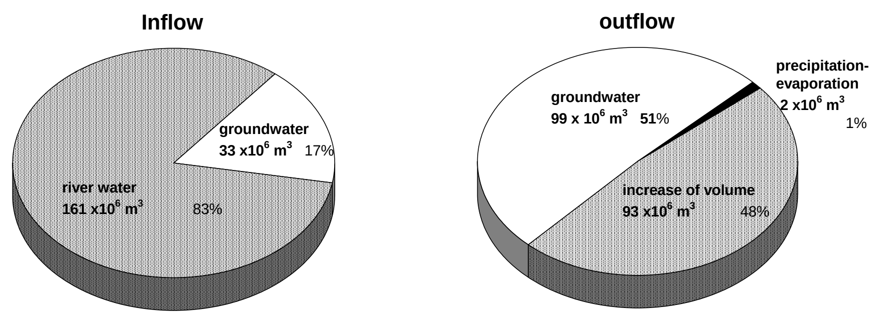

Figure 5. Elements of the water budget for Lake Bärwalde summing up the period of 5 years from 1998 to 2002.

Models Used

The monitoring of the water quality of the surface water and ground water bodies in the Lausitz post mining area can be combined with the water balances of the single lakes. This was done for all major lakes in the Lausitz area (Uhlmann et al., 2001). The water quality of the lakes is calculated with a two step algorithm. In a first step mass fluxes are calculated. This is done by a subdivision of the ground water inflow areas into uniform compartments that are represented with monitoring points (for example "inflow from Pleistocene aquifer in south", or "inflow from dump aquifer in south east"). The water balance using ground water flow models is calculated for the lakes by assigning control planes (to sum up the flow across them) at the ground water/lake interface, balancing the flow from the above mentioned uniform compartments. The second step is a reactive mixing step. The water and mass fluxes are mixed considering the geochemical constraints of an open system. Exchange of CO_2 and O_2 with the atmosphere, oxidation of Fe and precipitation of metal-hydroxide phases are considered as governing processes (Uhlmann, 1996; Werner and Luckner, 1997; Kalka und Märten, 2005). It has been shown that the regional ground water flow imposes a significant impact on the water quality of the mining lakes in the Lausitz area (Werner et al. 2001). Apart from the mass fluxes that are transported with the ground and surface water into the lakes, it is important to consider the mass fluxes created by leaching of the bank material and by erosion of slopes (Abel et al., 2000). Quantifying these erosive mass fluxes is a major problem in all of these calculations. The future development of these mass fluxes is unknown.

A shortcoming of this modeling approach is the neglect of the spatial distribution of the water quality. The lake is viewed as a 0 dimensional reactor (Fig. 6), embedded in a hydrologic system for which the water and mass fluxes are given as boundary fluxes, which is depicted by the arrows in Fig. 6 and 7. Lake Bärwalde is a dimictic lake, like most post mining lakes in the Lausitz area. A concept to combine the regional modeling of water fluxes and the processes within a lake was developed by Müller (2004). The mass fluxes are not lumped on a 0 dimensional reactor but instead passed on to a 2 dimensional lake model (represented in Fig. 7 by the grid used for the lake calculation). In Fig. 7 partial pressures of atmospheric gases are specified only for the top layer (lake surface), as hydrodynamic transport of these important constituents is calculated within the lake.

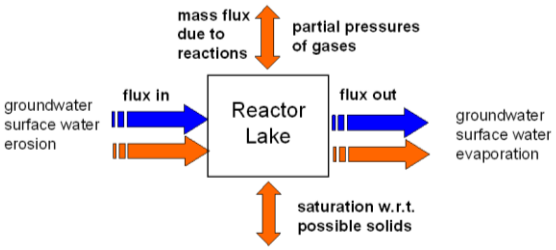

Figure 6. Regional mass balances combined with a mixing reactor approach.

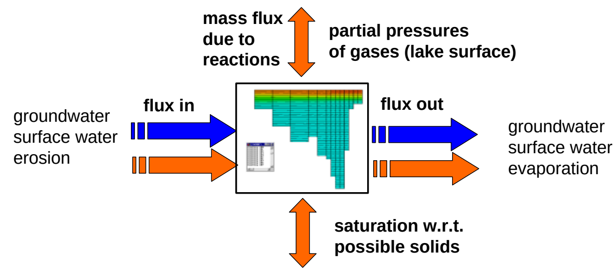

Figure 7. Regional mass balances combined with 2-D lake model.

The model MODGLUE (Müller, 2004) has been applied to Lake Bärwalde. MODGLUE is an integrated model for lake and groundwater quality. It is built on three existing and proven models that have been extended in their functionality and also includes newly developed modules. The three models are PCGEOFIM, CE-QUAL-W2 and PHREEQC.

Groundwater flow and transport is modeled with PCGEOFIM (Sames and Boy, 1999). There is a dynamic third type boundary condition (BC) that represents a lake in the ground water model. The head of the BC is adjusted by the model according to the specified volume-water-level-relationship. The lake volume is budgeted by the model from which the new lake water level can be deducted. This BC was used for the coupling of lake and groundwater in MODGLUE. Processes in the lake are modeled based on CE-QUAL-W2 (Cole and Buchak, 1995), a two-dimensional hydrodynamic and water quality model that solves the Navier-Stokes-Equation with a finite difference approach and uses the large eddy approximation for turbulence closure. In addition to the hydrodynamics that include thermal stratification, CE-QUAL-W2 can model transport of multiple species as well as biological reactions. This model is widely used and has been applied successfully in different parts of the world. It was modified to handle changing pH and alkalinity by coupling with a geochemical model. This was done to account for carbon limitation resulting from low pH as well as alkalinity production resulting from biological growth (Müller, 2004). An ideal composition of the algae that is composed and decomposed in the model had to be defined to include carbon in the nutrition consuming equations. This composition is a model input parameter that has to be defined by the user. A Redfield ratio of C : N : P of 106 : 16 : 1 was used in the Bärwalde simulation, being aware that "non ideal" composition is reported in literature (Kummert and Stumm, 1992). The speculated charge balance equation is used to calculate resulting changes in alkalinity and pH.

The geochemical speciation and reaction model PHREEQC (Parkhurst and Appelo, 1999) was applied for modeling geochemical processes such as kinetic redox reactions, mineral solution and precipitation as well as ion exchange reactions and the above mentioned integration of biological processes. Coupling of the three models employed software engineering techniques such as object-oriented programming, design patterns, hybrid programming, and object databases. Figure 8 shows the conceptual structure of MODGLUE.

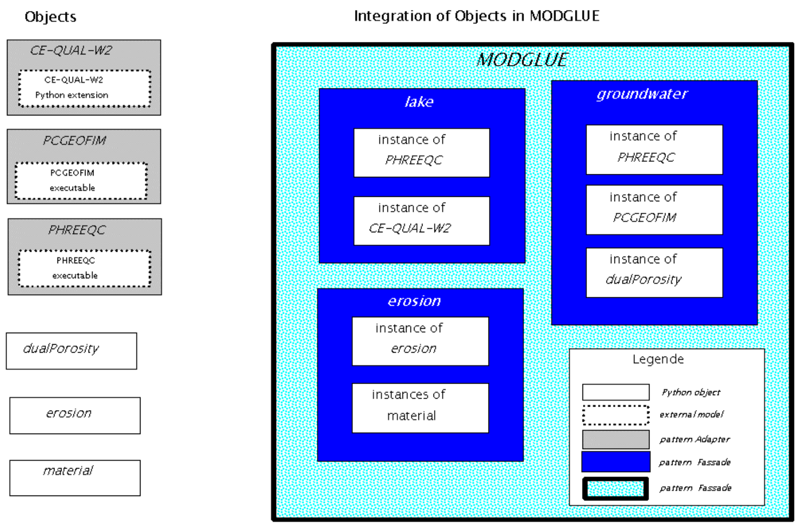

Figure 8. Objects of MODGLUE (From Müller and Werner, 2004).

The first three objects on the upper left of Fig. 8 are the existing models described above, wrapped-up with a layer implemented with the programming language Python. The wrapping utilized the design pattern adapter, turning the existing models into Python objects. The other objects are pure Python objects. They have been implemented to account for a dual porosity approach for release of acid mine drainage in the aquifers and dumps, and effects of bank erosion. The individual objects can be assembled in container objects. Each container uses the design pattern facade to give them a common interface for communicating with other objects. MODGLUE itself uses this pattern.

Modeling Results

The model was originally developed and tested in the years 1999 to 2002. A prediction was performed assuming that the surface water fluxes during flooding would be as high as observed in the years 2001 and 2002 (Fig. 9). Mass fluxes resulting from erosion and leaching were estimated based on the geometry of the shoreline and the acid releasing capacity of the sampled soils. The geometry of the shoreline is calculated during the runtime of the model. A specific feature of Lake Bärwalde is the shallow water zone that appears at water levels of 119 to 121 m a. s. l. as a patchwork of islands. These islands release more acid into the lake water compared to a water covered state (and have been eliminated in 2005 by a controlled detonation). An un-calibrated simulation showed that the acidic mass fluxes were underestimated in the model. The mass flux resulting from sediment leaching was used for calibration. A decreasing input of acidity from 1998 to 2002 was assigned. This corresponds to the early stage of the flooding, when the lake water was rising to the top of the mining dump.

In the original prediction the fast flooding was reaching the final water level in the year 2006. Neutralization of the lake water (titration acidity of 0 mmol charge/L) occurred in 2005 according to this scenario. This scenario could not be realized due to a lack of available surface water. In 2005 the model was updated with the surface water fluxes that had actually been used (Fig. 10). One result from this slow flooding is the existence of the islands within the lake. Figure 10 shows that neutralization does not occur as long as the surface water input is low, the water level is decreasing and the islands are not water covered.

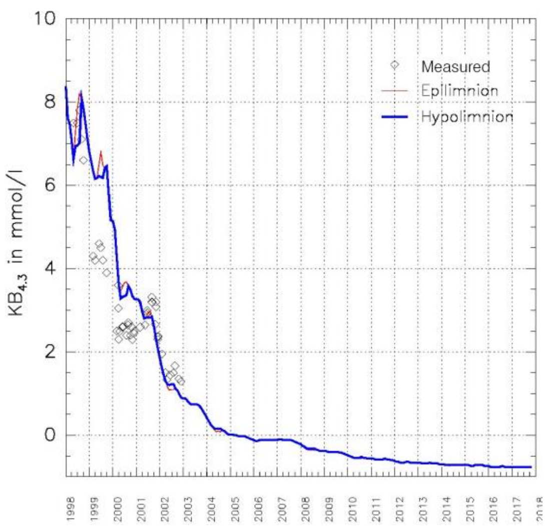

Figure 9. Acidity vs. time. Predicted and measured concentrations (2003). $KB_{4.3}$ is defined by the base consumption in a titration with endpoint pH 4.3, units are mmol charge/L.

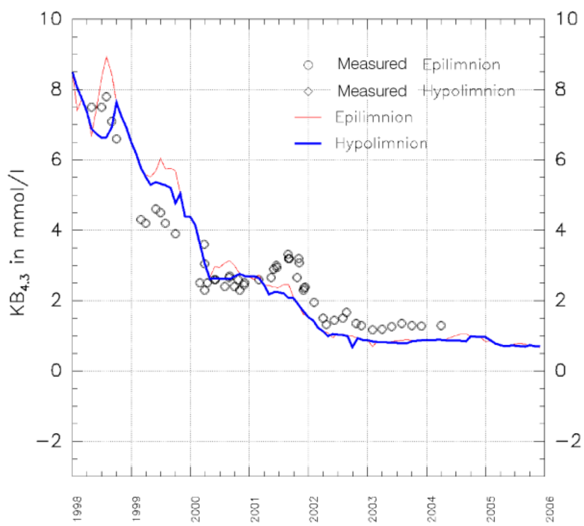

Figure 10. Acidity vs. time. Predicted and measured concentrations (2005).

The surface water input into the lake is managed with a weir. The results from this modeling study may be used to evaluate the environmental costs and benefits of water distribution. Since the available water is limited, a benefit on the one hand (maintaining minimum flow in the river), is causing a cost on the other hand (poor quality in the lake).

Conclusions

A complex model has been set up to predict the future development of the water quality of Pit Lake Bärwalde. Based on the assumption that flooding with surface water will be continued in the future, it is predicted that an acceptable water quality will be established in the near future. If a water treatment of the effluent water is necessary, it will be a temporary task. No permanent treatment plant has to be built according to our prediction.

It is shown in Fig. 9 and 10 that in the case of Lake Bärwalde a simulation using MODGLUE did not reveal significantly different water qualities for the two compartments (the epilimnion and the hypolimnion) of the lake. This might create the question, if the model could be simplified. A 1-D simulation is not regarded as a major simplification with respect to the meteorological and morphological data that has to be gathered. A 0-D model that is only able to reflect mean or rather effective conditions, could have predicted similar results. These effective conditions concern for example the concentrations of O_2 and CO_2. If the water and mass fluxes, received and discharged by the lake, would be close to a steady state, these effective conditions could be expressed by partial pressures of these gases constraining a 0-D system like a fully mixed body of water. Measured concentrations could be used to calculate these effective partial pressures. If the hydrologic fluxes are not constant over time, as expected in a flooding scenario, effective gas pressures are expected to change over time as well. These considerations support the use of a rather complicated and time consuming model that is able to reflect the stratification and mixing within the lake. For the Lausitz Pit Lakes from lignite mining on the other hand, it seems to be of prime importance to use 3-D ground water models to calculate the water balance, as these lakes are often located in highly permeable aquifers.

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