Multidisciplinary modeling of post mining lakes in Middle Germany

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Abstract

Open pit lignite mining in Middle Germany leaves numerous pits behind that form new lakes. These lakes provide new opportunities but new problems as well for the region. One major problem is the water quality of the lakes that is typically characterized by high acidity limiting the usage of the lakes. A new modeling tool, the coupled lake-groundwater water quality model MODGLUE was applied to several sites in Middle Germany. The tasks at this sites included long term water quality prognoses, evaluation of effective lake treatments, and investigation of shortcut flows that impact discharge water quality. Because of the complexity of processes and the strong interaction of the processes typically dealt with in individual models, coupled modeling proofed to be very advantageous and gave new insight into the problems.

1 Introduction

More than 50 years of intensive large scale open pit mining of lignite in Middle Germany left numerous pits behind that are being filled with rising groundwater, river water, and pumped groundwater. Thus, lakes are forming changing the landscape and creating new potentials for the use of the region. Since many lakes are in the vicinity of cities such as Leipzig, their use for recreation is very attractive and provides an interesting opportunity for the development of the region.

During mining considerable groundwater drawdown occurred because large amounts of groundwater were pumped to enable proper mining operation. Dewatered aquifers came into contact with oxygen from the inflowing air and underwent substantial chemical changes. Iron sulfides such as pyrite that are usually abundant in the aquifers oxidized and then dissolved as ferrous (divalent) iron and sulphate after groundwater rose again. Typically, this groundwater carries high acidity. When it flows into the freshly formed lakes, the ferrous iron it contains will be further oxidized into ferric iron frequently lowering the pH value to or below 3. Lakes with such low pH values are only partially suitable for many recreational activities. Furthermore, since many of the lakes will eventually discharge into nearby rivers requirements concerning water quality set by authorities have to be met which typically include a minimum pH value of 6.

2 Processes Determining the System Pit Lake

The processes determining the system of a pit-lake and its vicinity may be categorized by their type and their place of occurrence. There are flow, transport, and reaction processes that occur in natural and dump aquifers, lakes and lake benches.

The flow and transport of constituents through the natural aquifers are mainly determined by the geological properties of the subsurface. Mining dumps were created through human activities and are very different from natural aquifers. Their high heterogeneity in particular influences the flow and transport processes considerably and makes their quantification very difficult. The reaction of iron sulfides that mainly occur in the well aerated dumps is a major source of acidity that may be transported with the groundwater flow.

The major pit lakes reach depths of 20 meters or more. Therefore, hydrodynamics of these lakes show dimitic patterns with well mixed phases in spring and fall, stratified summer period as well as reversely stratified winter periods. Because the very limited exchange between the two layers in summer (epilimnon on top, hypolimnion below) they act as two nearly independent reactors with temporally different milieu conditions. Unlike in an aquifer, in a lake considerable biological activity such as primary production, i.e. algal growth might exist. However, if the pH value is low this activity will be considerably lower than in a neutral lake of similar size and nutrient level. The hydro chemical conditions in a lake are also very different from those in an aquifer. Through the intensive contact with the atmosphere, oxygen enters while carbon dioxide leaves the system creating aerobic conditions in the epilimnion. Therefore, transported dissolved constituents such as ferrous iron will oxidize, precipitate e.g. in the form of iron hydroxide and lower the pH-value of the lake water.

Bench of lakes often consist of dump materials. Since these materials may contain large amounts of oxidized iron sulphates they are a potential source of acidity. Different kinds of erosion processes such as wind wave and precipitation-induced erosion as well as bench slides may introduce considerable amounts of bench materials into lakes with strong impacts on lake water quality.

Exchange processes with dumps located below lake water levels are also a source of acidity for a pit lake joining the other two sources, groundwater flowing through dump areas and erosion processes. The importance of these sources may vary considerably from lake to lake. Determining the size of the sources and the rates by which they affect lake water quality is a difficult task and requires further investigations.

In order to achieve an acceptable water quality in many lakes, considerable human interventions are necessary. By far the most important measure is to fill the lakes with river water or pumped groundwater from dewatering of active mines. This has several advantages. Firstly, the filling water typically has alkalinity that improves pH conditions. Secondly, the rising lake water table reduces the hydraulic gradient of inflowing groundwater which leads to less groundwater inflow and therefore of less potentially acidic water. Lastly, a fast rising lake water table results in lower requirements to the bench stability because the water pressure stabilizes the bench slopes that might otherwise become unstable when exposed for longer periods. This may considerably reduce costs for bench restructuring.

Unfortunately, the amount of available river water is limited. Annual precipitation in the region averages at 500 to 600 mm. Excess water that could be used for lake filling is frequently only available during winter months and needs to be shared among lakes. Therefore, chemical treatment of lake water itself or discharged water to rivers is gaining more importance as the lakes reach their final. Chemical treatment of lakes is designed to change chemical processes in a lake and therefore has to be considered as humanly induced process.

The processes involved are complex and often tightly interwoven. Knowledge from many scientific fields is required to understand these processes. Major fields are hydrology, hydro-geo-chemistry, limnology, hydrogeology, fluid dynamics, meteorology as wells soil mechanics.

3 Tools and Methods

As it is often extremely difficult to anticipate the outcome of actual interventions it is necessary to model all the processes that are determining the system “pit lake and its vicinity”. Because there is a strong interaction of processes that are typically modeled individually in different models, coupling of these models becomes necessary.

The newly developed model MODGLUE [5] is an attempt to capture all determining processes and their interactions in one model. Three existing models, CE-QUAL-W2 [2], PCGEOFIM [8, 6], and PHREEQC [7] were coupled, partially modified, and extended. Figure 1 shows a schematic of the model. CE-QUAL-W2 is a two-dimensional, laterally averaged hydrodynamic and water quality model. It solves the Navier Stokes equation using the large eddy diffusion approach. Its water quality module is designed for natural lakes with neutral pH dominated by biological processes such as primary production and nutrient cycles as well as atmospheric exchange of oxygen. PHREEQC is a hydrochemistry model that was coupled with CE-QUAL-W2 to enable modeling of chemical processes at low pH values such as pH-dependent iron oxidation and subsequent precipitation of ferrous hydroxides, pH-dependent CO_2 exchange with the atmosphere, and other kinetic redoxreactions. PCGEOFIM is a three-dimensional finite volume groundwater flow and transport model that provides many features that are especially useful for mining influenced groundwater systems. It provides stable modeling of rising groundwater over several model layers, a special boundary condition for pit lakes that changes its head as a function of lake water volume, as well as other boundary conditions that can account for technical interventions such as regulated lake inflows and outflows according to defined conditions.

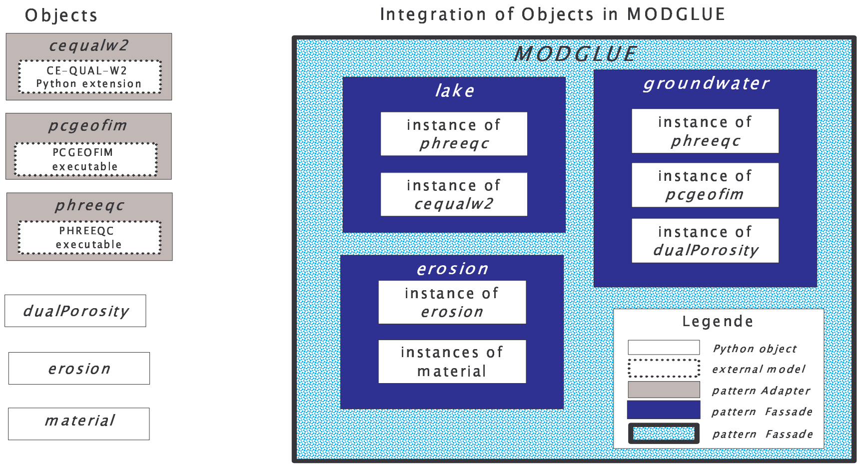

Figure 1: Objects in MODGLUE

4 Model Implementation

The implementation of MODGLUE is based on object-oriented programming techniques and makes use of design patterns. Figure 1 shows the objects and their combination to compound objects according to design patterns. Some of the existing models have been heavily refactored and turned into extensions for the Python programming language [4]. Thus, about 50 man years of programming could be integrated into the new system. Due to the demand for CPU-time the geochemical calculation, which take the majority of the computing time were parallized using the pyro framework [3]. The parallized part of the model shows performance improvements of 95 % for a medium-sized problem and even more for larger problems.

The model system was designed to be easily extensible. This anticipated flexibility proofed very valuable because most of the tasks, explained in more detail in the next section, required modification or extensions of model capabilities to account for specific needs at the site.

6 Application to sites in mining regions Middle Germany and Lausitz

MODGLUE has been successfully applied to five lakes in Middle Germany and one (Lake Bärwalde) in the Lausitz mining region for different task such as long term water quality prognosis, evaluation of effective lake treatments, and investigation of shortcut flows that impact discharge water quality. Each of this model application has unique requirements that are site specific and made modifications and extensions of the model necessary. Table 1 provides an overview of the sites were MODGLUE was used.

Table 1: MODGLUE application sites and tasks

Site	**Task**
Lake Cospuden	Hydrodynamic modeling
Lake Bärwalde	Water quality prediction
Lake Bockwitz	Water quality treatment evaluation
Lake-System Hain-Kahnsdorf	Hydraulic shortcut investigations
Lake Zwenkau	Water quality prediction
Lake Runstädt	Density driven groundwater in and outflow, long term water quality prediction

Lake Cospuden is an already filled lake located directly south of Leipzig that has been used for several years mainly for recreational purposes. It served as a first investigation site to demonstrate the abilities of MODGLUE to model the hydrodynamic behavior of a mining lake. The model reproduced the measured yearly change of the depth-temperature relation very well. This model results suggest, that the hydrodynamic situation at this lake can be accounted for in MODGLUE.

Lake Bärwalde is a lake in the Lausitz mining region, which is located about 150 km north east of the Middle Germany mining region. This lake was used as a sample site for model development [5]. Besides hydrodynamics in the lake, groundwater in and outflows both in terms of volume and of water quality were considered by inclusion of three dimensional groundwater flow model. Furthermore, chemically and biologically induced water quality changes were modeled. Erosion was included in the model by calculation of movement of bench material into the lake as well as effects of this material on chemical water quality. Inflowing rivers used to fill the lake were accounted for also in terms of water volume and water quality. It was possible to make first prediction of the development of water quality. Modeling results are in agreement with recent measurements of water quality from the last two years.

Lake Bockwitz is a smaller lake with about 18 million m^3 in its final state (as compared to Bärwalde with about 160 million m^3). Filling with river water is no option to improve its water quality that is characterized by pH-values as low as 2.7. Therefore, a treatment of the lake water with sodium carbonate was conducted. MODGLUE was used to investigate the hydrodynamic distribution of the sodium carbonate which was introduced in the lake as powder. The predictions of MODGLUE showed that the mixed in sodium carbonate will distribute throughout the entire lake if it is introduced at a location found by scenario analyses with the model. Current measurements of water quality confirm this prediction. Presently a water quality modeling study is running at this site.

The **Lake-System Hain-Kahnsdorf** south of Leipzig consist of two adjacent lakes, Hain, which is expected to become neutral in its final filled state, and Lake Kahnsdorf, which will stay acidic for the next decades. Water from Lake Kahnsdorf has to flow into Lake Hain. Since the amount is small compared to the lake volume this poses no problem if the water is well mixed with the whole lake volume. But the inflow point is close to the point of discharge to a river. If the water shortcuts, acidic water might reach the river. This has to be avoided because of regulatory requirements. Scenario analyses with MODGLUE showed that an inflow at greater depth will result in an acceptable water quality at the point of discharge.

Lake Zwenkau, located south of Lake Cospuden, will be filled with river and pumped groundwater during the following years. Even though the current water body consists of only about 10 % of the final lake volume an estimate of the future water quality had to be made. MODGLUE was used to model the development of lake water quality over a period of 20 years. Water sources considered include river inflows, inflowing groundwater the amount of which was calculated by a separate groundwater model, as well as pumped groundwater from dewatering of active mines in the region. The lake was split into three sub lakes, accounting for the morphology of the lake and providing quasi three dimensional capabilities of the otherwise two dimensional lake model. At this site it was predicted that the dump underlying the future lake will be the major source of acidity. The modeling with MODGLUE brought some new insight into problem leading to new kind of field investigations that are targeted at quantifying the acidity release of the dump below the lake.

Lake Runstädt is located west of Leipzig. It's pit is partially filled with waste products from fertilizer production. This waste mainly consists of ammonia and might cause water quality problems. Currently, deep water aeration is necessary to keep the dissolved oxygen levels above 4 mg/L at the lake bottom. The restoration strategy at the lake aims at a lake without outflows that receives only small amounts of groundwater from the surroundings and in long term evaporates this amount keeping a stable lake water level. MODGLUE is used in active research project. It is being coupled with MODMST [1], a density driven three dimensional groundwater model. The objective is to model density driven flow between lake and groundwater that might occur if a monimolimnion, a layer with higher density above the lake bottom, forms and may cause flow out of the lake even though hydraulic gradient indicate otherwise.

6 Conclusions

Modeling of pit lake water quality is a complex task. MODGLUE proved to be a valuable tool that helps to get a deeper insight into system processes, to predict future developments, and to assess the impact of human interventions in the system. A mutual exchange between modeling and field investigations leads to an incremental approach that yields results that increase the agreement between model and reality with each iteration.

The application of MODGLUE also proved to be helpful for quantifying the different sources. Although predicting absolute values has significant uncertainty, a ranking of sources according to their potential and release rate is possible. Based on these modeling results further field investigation can be target to the most dominant processes. In turn the result of field measurements combined with lab investigations of site materials can be used as improved model input leading to better modeling results. This iterative approach enables a stepwise refinement of system knowledge combining both modeling and field measurements. Consequently, to provide useful results, modeling of pit lakes has to be a continuing activity. Using this approach, more and more about the system can be revealed as modeling results and field investigations approach within reasonable limits.

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