Characterizing Water Quality of Pit Lake through Modeling

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Abstract One common issue of open pit lakes is the water quality which is often dominated by acid mine drainage and therefore unsuitable for many desired purposes. To improve the water quality, it is important to understand and quantify the processes. The approach reported here focuses on a sophisticated model that has been developed and applied to different lakes over the last decade. The model development followed these guidelines: (1) using well-established existing models wherever possible, (2) adding functionality whenever necessary, and (3) adapting the model to the site-specific needs. This was achieved with modern software development methodologies such as object-oriented programming, integration of several programming languages in one code as well as application of a modern scripting language for all coupling tasks. The model takes into account of all relevant in-lake processes as well as sinks and sources of acidity fluxes. It is based on CE-QUAL-W2 and PHREEQC and coupled to two groundwater models (PCGEOFIM and MODMST). Lakes can be represented as two- or quasi-three-dimensional structures. Wind-induced hydrodynamics are modeled along with density-driven stratification and biological and chemical water quality changes. Acidity sources such as bank erosion, release from the sediment and groundwater inflow can be modeled with arbitrary spatial variability. The model has been successfully applied to lakes with different characteristics. Both short and long term investigations over decades were carried out. It was used to optimize the amount and application schedule of chemicals for lake neutralization. The iteration cycle "measurement-modeling-evaluation-re-measurement" brought new insights into the site-specific processes in each lake. The model is in continuous development. Its designed-in flexibility has proven to be very valuable for the adaption to initially unanticipated challenges.

Key Words pit lakes, open cast mining, water quality modeling, acid mine drainage, Pit Lake Model

Introduction

The water quality open pit lakes is often unsuitable for many purposes such as recreation or storage for balancing droughts and floods. This is due to the acid mine drainage of a lake receives. Measures to improve water quality are possible but need to be based on knowledge over what source are most significant and what quantities of acidity and alkalinity are to be expected over which time periods.

There are several sources of acidic waters for a pit lake. Besides the groundwater inflow from dump areas, surface water runoff and the associated erosion as well as wind wave-caused erosion and substance released from submerged sediments can be significant sources. On the other hand, inflowing water diverted from rivers can introduce alkalinity into the lake.

A variety of chemical reactions need to be considered. The iron and aluminum in the lake water form buffering systems that determine the pH in the acid range. Precipitation of iron and aluminum hydroxides is also very important. The gas exchange with the atmosphere has a significant impact on lake water quality. Besides oxygen, carbon dioxide plays an important role since it outgases at low pH conditions in the lake leading to very low carbon dioxide concentrations in the lake water. While phosphorus is the limiting nutrient in most natural lakes, carbon often becomes limiting for algae growth in acidic lakes. Therefore, lake water quality models designed for natural lakes usually need to be modified to be useful for pit lake modeling.

In addition, interventions to improve water quality such as addition of alkaline chemical substances may be advantageous for pit lakes. Different technologies such as distribution of substances by boat or application from land-based stations are used.

The objective this paper is to give an overview of the modeling technique and of the type of results that can be obtained from modeling. The results can help to support decision making and to control measures for improvement of water quality.

Pit Lake Model

The Pit Lake Model (Müller 2004) allows the representation of all processes described above. Rather than developing a totally new model, established models were engaged, coupled, and extended. Software engineering techniques were used to produce an integrated model that is also flexible and allows adaption to site-specific needs. The model has been extended in functionality with each application and applied to several lakes (Müller et al. 2008, Werner et. al. 2008).

The Pit Lake Model couples CE-QUAL-W2 (Cole and Buchak 1995), PHREEQC (Parkhurst and Appelo 1999), one of the groundwater models PCGEOFIM (Müller et al. 2003, Sames et al. 2010) or MODMST (Boy et al. 2001), as well as several newly developed sub models for erosion, sediment release, and treatment. CE-QUAL-W2 is a water quality model that allows two-dimensional and quasi-three-dimensional models for lakes, reservoirs and rivers. It is a internationally widely used model covering all import processes such as flow based on a finite difference solution of the Navier-Stokes-Equation, transport, and water quality calculations including nutrient cycling and algae growth. It calculates the water density from the water temperature and the solute concentrations linking water quality and flow calculations. PHREEQC is a widely used hydrogeochemical model for calculating a great variety of chemical reactions. The extensible species database in combination with the possibility to define own kinetic reactions allows adapting PHREEQC to special needs. PCGEOFIM is a finite volume groundwater flow and transport model that is designed for the special needs of mining and post mining areas. It has a boundary condition “lake” that uses dynamic boundary Cauchy conditions. It recalculates the lake water level according to a water-level-volume relationship after budgeting all sinks and sources. This mechanism was utilized for coupling with CE-QUAL-W2. MODMST is a groundwater flow and transport model for density-driven flow. It can be used as an alternative groundwater model instead of PCGEOFIM when density effects are of importance.

In addition to the coupling of existing models, new algorithms were developed to account for other processes. The influence of erosion caused by surface runoff and wind waves on water quality is modeled regarding solutes in the pore space of eroded material as well as its cation exchange capacity. It is also possible to compute the release of substances from the submerged sediments as a function of time or depending on the composition of the lake water above ground. Both erosion and sediment release require on-site measurements and laboratory studies to yield the model parameters. The model allows the spatial distribution of parameters in zones that may consist of any number of lake cells.

Treatment of lake water is implemented as addition of substances at specified model cells with time varying rates. With this method aeration near the lake bottom as well as addition of sodium carbonate at the lake surface could be successfully modeled.

Applications

The Pit Lake Model has been applied to various lakes in Germany and Australia. Experience shows that even though the principal processes are the same, each site is different from the other often to an extent that requires additions to the modeling software itself. Examples for these site

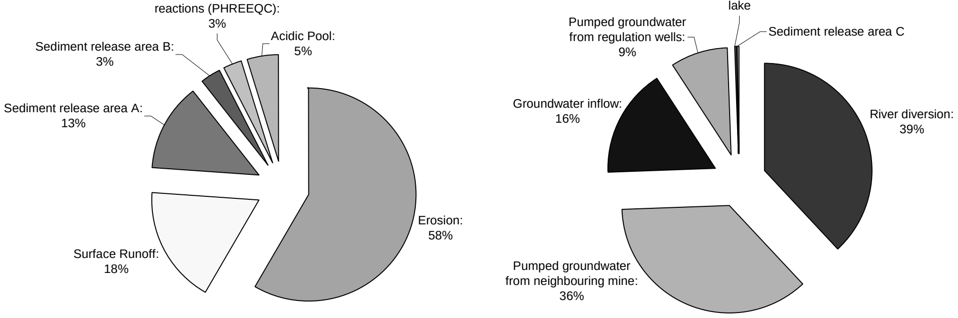
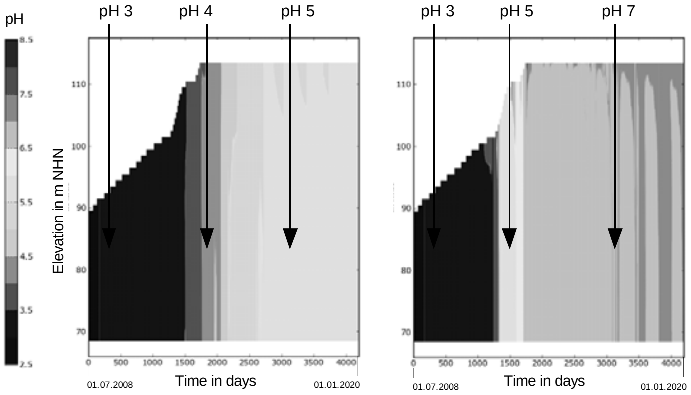


***Figure 1** Sources of acidity and alkalinity and their fractions over a five-year-period*



river diversion, no technical initial neutralisation

river diversion, technical initial neutralisation

Figure 2 *Time-depth diagram of pH at deepest point*

specifics are special lake geometries, very fast filling with river water, merging of sub lakes, or requirements of lake treatment strategies.

The following modeling results are obtained for a lake in Germany. Due to its complicate shape the lake was subdivide into three connected sub lakes using CE-QUAL-W2's branches. This quasi-three-dimensional setup allowed modeling the development of the lake for wide ranges of water levels.

One important result of lake modeling is the attribution of acidity and alkalinity to the different sources or sinks. An example result in fig. 1 clearly shows the domination of erosion-caused acidity. Furthermore, the main source of alkalinity can be indentified as the water diverted from a regional river and pumped groundwater from a neighbouring mine. This type of analysis can be done for different time periods showing the development of sinks and sources over time.

Another interesting result is the development of the pH in the lake. As shown in fig. 2, there is a significant difference in whether technical neutralisation, i.e. addition of substances is applied (right) or not (left). This kind of analysis can be performed for different locations in the lake investigating the spatial variability.

In addition to the pH, base capacity is important to describe the lake water quality that also quantifies buffering effects. The development of the base capacity over time can be seen in fig. 3.

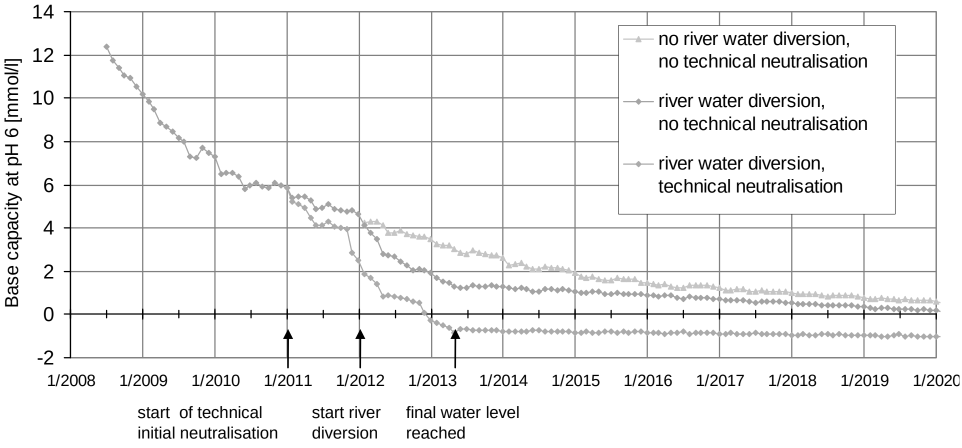


Figure 3 *Development of base capacity over time for different scenarios*

The difference between the calculations without any measures, with addition of diverted river water, and with additional technical neutralization can be clearly seen. Neutral conditions can only be reached if technical neutralization is applied. Other scenario calculations helped to decide if a large addition or several small additions are optimal in terms of neutralization effect and long term water quality development.

Currently, the Pit Lake Model is applied to three of the Collie Lakes in Western Australia. First results are promising. For instance, the decline in pH after addition of water diverted from a river has stopped in one of the lakes. This effect could be reproduced with the model setup for this site suggesting that the main mechanisms that determine water quality are reflected in the model.

Model validation

The algorithms for the physical and chemical processes provide reproducible and stable results. The problem of model validation lies in the parameters. Even simple data such as amounts of inflows from rivers and pumped groundwater can have measurement errors. The range of possible values for erosion and sediment release data is much wider. Data from sampling single points are applied over large areas. Furthermore, laboratory data obtained from experiments over a few weeks are extrapolated to years.

Several strategies can help to mitigate these problems. Results of model sensitivity analyses help to direct measurements and laboratory experiments. Better measured values in turn help to improve modeling. Models need to be continuously updated with newly measured values. This is especially true for lakes with fast rising water tables. Even though absolute modeling results contain parameter-induced uncertainties, modeling allows for sensitivity analysis and comparison of alternative solutions.

Conclusions

The Pit Lake Model proves to be a very useful tool for quantifying water quality of pit lakes and possible strategies to improve upon it. This holds true for different types of lakes in Germany and Australia and can be attributed to the reliability and features of the existing modeling software, the integrating coupling as well as the flexibility to adapt the model to site-specific needs. The Pit Lake Model is flexible enough to solve similar problems at pit lakes with additional requirements.

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