Modelling of the hydraulic behaviour of deep mines in regional aquifer systems

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Abstract The flooding of deep mines is part of the remediation concepts for uranium mining legacies in Germany. The prediction of hydraulic and geochemical environmental impacts on the regional groundwater flow is required as a precondition for a safe and economically feasible end of any deep mining activity as well as to gain the necessary approval. As in the presented Königstein case modelling the hydraulic impact of deep mine flooding on a regional scale using commercially available groundwater modelling software usually requires various workarounds. Problems mainly arise because of different hydraulic behaviour of mine workings and aquifers resulting in differences concerning the necessary temporal and spatial discretisation of the mine and the partially saturated aquifers. Furthermore, there are no off-the-shelf solutions available allowing to model both the hydraulic and geochemical conditions on a regional scale. The paper outlines the general modelling concept for the Königstein deep mine site including a description of the applied modelling tools and their interaction. For hydraulic modelling of the mine flooding a general mine boundary condition is used which was implemented in the numerical groundwater modelling code SPRING. The contaminant release is calculated by a box model developed for the Königstein mine. The applied models and concepts are continuously verified based on monitoring results gathered during the flooding of separated mine fields.

Key Words underground mine flooding, modelling concept, regional scale, case study

Introduction

Predicting the hydraulic and geochemical conditions developing during and after the flooding of deep mines within flooded mine workings and their surrounding aquifers is challenging. Relevant processes mostly appear on various temporal and spatial scales usually not allowing to be represented in one model but requiring a joint conceptual approach. Remediation of the Königstein mine has been continuing between the conceptual phase and its finalisation over a period of several years. Within the uranium mining and milling rehabilitation project of the Wismut GmbH in Germany the opportunity to develop a broad modelling approach to cover the significant medium and long-term processes is given.

The Königstein mine is situated in an ecologically sensitive and densely populated area close to the capital of the German Federal State of Saxony, Dresden. Between the early sixties and 1990 about 19,000 t of uranium were produced initially by conventional mining and later by in-situ leaching (ISL). Unlike other ISL-operations in Königstein leaching was applied within the underground mine. Blocks of ore bearing rocks were enclosed by mine workings containing feeding and drainage systems for the leaching fluid. Uranium mineralization was found in the deepest of a regional vertical sequence of sandstone aquifers. The sandstone aquifers are separated by less permeable aquicludes. Pore water in the leached sandstone blocks is characterised by pH 2.0, EC 700 mV, 10 g/L SO_4^{2-}, 3 mg/L Fe, 200 mg/L Zn, 200 mg/L U and 300 mg/L Al (Jenk et al. 2008).

It is the aim of the remediation concept to wash out the main part of the mobile contaminants from the mine in a controlled way to avoid contamination of the surrounding aquifers. Especially the overlying so called 3rd aquifer is a potential drinking water resource. With rising mine water level to natural conditions water would flow from the mine into the surrounding aquifers. Predictions of the resulting water quality are necessary for licensing applications. Remediation scenarios have to be evaluated to find an optimal solution for the mine closure.

Remediation of the Königstein mine follows a stepwise approach with the flooding of isolated mine parts while water pumping still ensures that no outflow of contaminated mine waters occur into the surrounding aquifers. It is planned to finally achieve natural flow conditions without active measures where, however, groundwater would be influenced by mine water.

Modelling Approach and Implementation

It became clear that no ready to use modelling tool was available for the prediction of both the hydraulic and geochemical conditions. Therefore, a modelling concept had to be developed and continuously further refined. It consists of various models representing the relevant processes during mine flooding which are connected at predefined interfaces.

Precondition for any modelling activity is a conceptual understanding of the site and the relevant processes. At the Königstein mine hydrogeological and hydraulic understanding has been developing since mining started several decades ago. Based on review of this knowledge base and additional measurements a well founded understanding of the regional groundwater flow and a vast number of level and flow measurements as a basis for a regional flow model exist. This conceptual understanding of the natural and anthropogenic conditions is summarised as Conceptual Site Model (fig.1) being the basis for all analytical and numerical models of the Konigstein site.

Using the finite element (FE) modelling code SPRING a regional flow model was prepared for the site. However, modelling the interaction between water levels in the flooded mine and the surrounding aquifers using available modelling tools requires various workarounds by adopting e.g. special k values to represent of the hydraulic connections by mine workings. These workarounds may lead to numerical instabilities. On the other hand detailed modelling of mine workings in the regional flow model is not feasible.

It was decided to extend the model code with a so called mine boundary condition allowing to describe mines or separate mining fields within a finite element mesh. This condition could be assigned to any part of the model grid. For model cells pooled in such a way it is assumed that one water level occurs and a water balance of in- and outflows is calculated for each time step. A relationship between mine water level and storage volume has to be defined for the single mining fields. Based on this relationship and the water balance calculated a new water level is assigned to the cells of the concerning mining field. This approach allows to include the interaction between mine flooding and the conditions in the surrounding aquifers but does not require a detailed description of the open mine workings or any other workaround.

The regional flow model is a combined saturated/ unsaturated model applying the Van-Genuchten-functions (van Genuchten 1980) allowing to describe the respective free water table in the relevant aquifers of the stratified sandstone aquifer system. In total the model includes about 400000 knots on 19 layers with a finer vertical discretisation of the relevant 2 deep aquifers

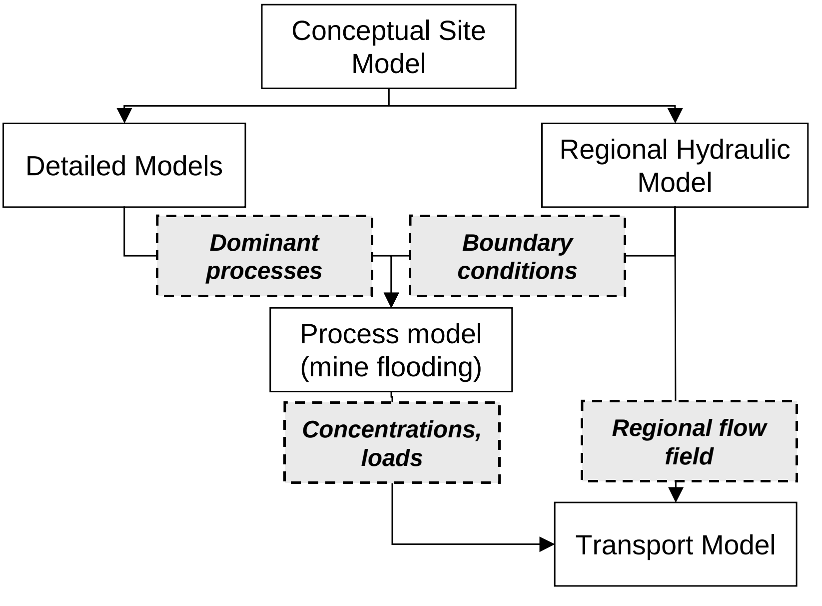

Figure 1 Modelling approach for the Königstein mine

and the aquiclude in between. Relevant tectonical elements such as fracture zones and anthropogenic hydraulic connections between the aquifers are separately implemented.

The regional hydraulic model was calibrated based on the water level measurements and the mine inflow during the active mining starting in 1964. This phase is characterised by the drawdown of the groundwater table. Having both detailed water level and groundwater inflow measurements for a complex flow system the model calibration became very time-consuming. Detailed monitoring measurements during the remediation phase from 1990 were used for continuous model verification. This phase included the stabilisation of the hydraulic conditions between 1990 and 2001 followed by filling of the groundwater depressions in the aquifers as a result of the stepwise mine flooding. Model adjustments were required due to a different hydraulic behaviour compared to the drawdown and partly changed positions of the monitoring points. Using the hydraulic model the development of the regional flow field could be predicted for various flooding options providing the necessary information on hydraulic boundary conditions for other models (fig. 1).

To describe the contaminant release from the mine the box model FLOODING was developed. This box models covers the mine within its contour while water in- and outflows through this contour are defined as boundary conditions taken from the regional flow model. The single boxes of the model represent certain parts of the mine and have an internal structure. They include the volume of the mine workings and the saturated and unsaturated pore volume of the rocks. In the model the contaminants are contained in the pore water of the rocks and as secondary minerals in the mine workings.

Flooding of the mine leads to a dissolution of the secondary minerals and dilution of the pore water. At the beginning the contaminant release from the flooded mine is dominated by the advective transport of the dissolved contaminants in the open mine workings. Flushing out of the hydraulically well connected mine openings results in a peak of released contaminant concentrations and loads. The long-term release of contaminants depends on slower processes. It was found in detailed models and fields tests of separated mine parts that in the Königstein mine density driven flow will be the relevant process for medium to long-term contaminant release. Diffusive processes connecting stagnant parts are less important.

In this process model FLOODING the geochemical conditions during the mine flooding are calculated. Therefore, apart from mixing calculations a PHREEQC routine was included to represent the effect of relevant reactions leading to changes of milieu parameters and concentrations of the single species.

As a result of both geochemical mine and regional flow models a representation of the regional flow conditions and the expected contaminant releases from the mine are predictable for certain flooding scenarios. At present several 1D-flow models are prepared based on the Transport option of PHREEQC to exemplary predict the hydrochemical conditions within the affected aquifers along an expected flow path. The results of the regional flow and geochemical mine flooding models of the define the boundary conditions for these reactive transport models. The results of the transport modelling in the surrounding aquifers is a precondition for the approval of the final remediation steps by the authorities.

Parametrisation

A modelling concept does not only account for appropriate modelling tools but also has to ensure a consistent parameterisation of the models. This is where again the conceptual understanding of the site is of importance. In the Königstein case a broad historic data set exists. However, during the active mining monitoring had a different focus compared to the remediation phase. While the hydraulic characteristics were of importance in both periods geochemical analysis was mainly economically focussed on the uranium content of the rock material in the past. Proper prediction of the geochemical conditions influenced by the mine flooding however requires a broad spectrum of initial parameters. Therefore the characterisation of the geochemical conditions within the mine but also in the surrounding aquifer became a main task during planning and implementation of remediation measures.

For the characterisation of the relevant contaminant release processes and the estimation of the available contaminant potential an experimental flooding of isolated mine areas had been conducted between 1993 and 2000. The monitoring of the water level rise and subsequent flushing out of contaminants was an important basis for the integral parametrisation of the geochemical mine flooding model. As it was shown in the later flooding of further mine areas the calibration of the model based on the experimental flooding was adequate also for the up-scaled prediction of the flooding of bigger mine parts in terms of the mobilised contaminant loads and concentrations. It demonstrated that the main processes influencing the contaminant release are considered in the modelling approach.

Because of the stepwise flooding of the mine the modelling tools could be continuously verified and if necessary adjusted in more detail. The modelling approach allows easily to calculate various flooding scenarios also with variation of certain parameters. This allows to analyse the model sensitivity separately for the different models in an effective manner where the effects of single parameter changes could be more clearly distinguished.

Conclusions

Predicting of the impact of deep mine flooding requires the description of the expected hydraulic and geochemical impacts on the surrounding aquifers. Because of the available modelling tools and the problem that relevant processes are linked to different scales a consistent and robust modelling approach is necessary. In the described case different models representing various scales were combined in a joint modelling approach.

It was found that special effort should be paid to the conceptual understanding of the site including the identification of the main processes in the complex system. These processes have to be accounted for in the modelling approach requiring a proper characterization of the necessary input parameters. It is necessary to determine ranges of the single parameters to allow plausible parameter variations during calibration and to account for their sensitivity within the predictions. Especially the concentration of reactive geochemical components such as calcite could vary in the order of magnitudes within a regional flow system strongly influencing the release and propagation of contaminants.

The presented modelling concept mainly uses commercially available modelling tools and takes into account the complex system of the mine and surrounding aquifers. To avoid numerical and conceptual problems resulting from the model discretisation a combination of different models is used with a clearly defined interface ensuring a consistent transfer of parameters and boundary conditions. These models describe the essential hydraulic and geochemical processes on the respective model scale.

To model the flooding of a mine or separate mining fields within a regional groundwater flow the SPRING model code was amended by a specific mine boundary condition allowing to represent the hydraulic effect of the connected mine workings and the volumes of open mine workings and pore spaces and their vertical distribution.

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References

Jenk U, Nindel K, Zimmermann U (2008) Underground in-situ mine water treatment in a flooded uranium mine at the WISMUT Königstein site – motivation activities and outlook. In: Merkel B, Hasche-Berger A (Eds), 2008 Uranium Mining and Hydrogeology, Springer Heidelberg, p 431 – 436

Van Genuchten T (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Of America Journal, p 892 – 898