FLOODING OF THE KÖNIGSTEIN UNDERGROUND MINE HYDRAULIC AND GEOCHEMICAL MODELLING APPROACH

ZATÁPĚNÍ HLUBINNÉHO DOLU KÖNIGSTEIN HYDRAULICKÉ A GEOCHEMICKÉ MODELOVÁNÍ

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Abstract

Uranium was produced in the Königstein mine by conventional mining as well as underground in-situ leaching activity from a sandstone aquifer between 1964 and 1990. Due to the chemical mining and the secondary effect of pyrite oxidation the pore water of the rock matrix has a pH of less than 2 and a high content of among others uranium, iron and sulphate. Another source of contaminants are soluble minerals which precipitated in open mine workings. They will dissolve during the flooding and generate a contaminant peak right after the beginning of the flooding of open mine spaces. The remediation of the mine should aim for the restoration of the natural groundwater flow in the regional flow system.

Abstrakt

V letech 1964 – 1990 probíhala na Dole Königstein těžba uranu jak konvenční dobývací metodou, tak i loužením in-situ z pískovcových kolektorů. V důsledku této metody chemické těžby a sekundárního efektu - oxidace pyritu, má pórová voda horninové matrice pH nižší než 2 a vysoké obsahy uranu, železa a síranů. Dalším zdrojem kontaminace důlních vod jsou rozpustné evaporáty, jež jsou vysráženy v otevřených suchých důlních dílech. Tyto se v průběhu zatápění zpětně rozpouštějí a tvoří maximální podíl kontaminační zátěže v počátečních fázích zatápění důlních prostor. Důlní vody z ložiska jsou čerpány prostřednictvím vrtů a vyváděny k přečistění na úpravnu. Cílem sanace dolu je revitalizace hornicky postižené oblasti, tj. obnovení přírodních podmínek proudění a kvality podzemních vod.

Key words: flooded mines, mine water, hydrogeological and geochemical modelling.

1 INTRODUCTION

Uranium was produced in the Königstein mine by conventional mining as well as underground in-situ leaching activity from a sandstone aquifer between 1964 and 1990. Due to the chemical mining and the secondary effect of pyrite oxidation the pore water of the rock matrix has a pH of less than 2 and a high content of among others uranium, iron and sulphate. Another source of contaminants are soluble minerals which precipitated in open mine workings. They will dissolve during the flooding and generate a contaminant peak right after the beginning of the flooding of open mine spaces.

The remediation of the mine should aim for the restoration of the natural groundwater flow in the regional flow system. Flooding the mine leads to the release of contaminants. At present, the flooding of the hydraulically isolated mine is conducted. All drained waters are collected in a control drift downstream from the mine body and pumped through wells to the water treatment plant. By managing the water table in the control drift the outflow of flood (mine) water into the 4th aquifer is controlled. By further rise of the mine water table towards hydraulically stable conditions the water inflow from the covering 3rd aquifer will be further reduced by a change of flow direction, eventually resulting in an outflow of mine water into the upper aquifer.

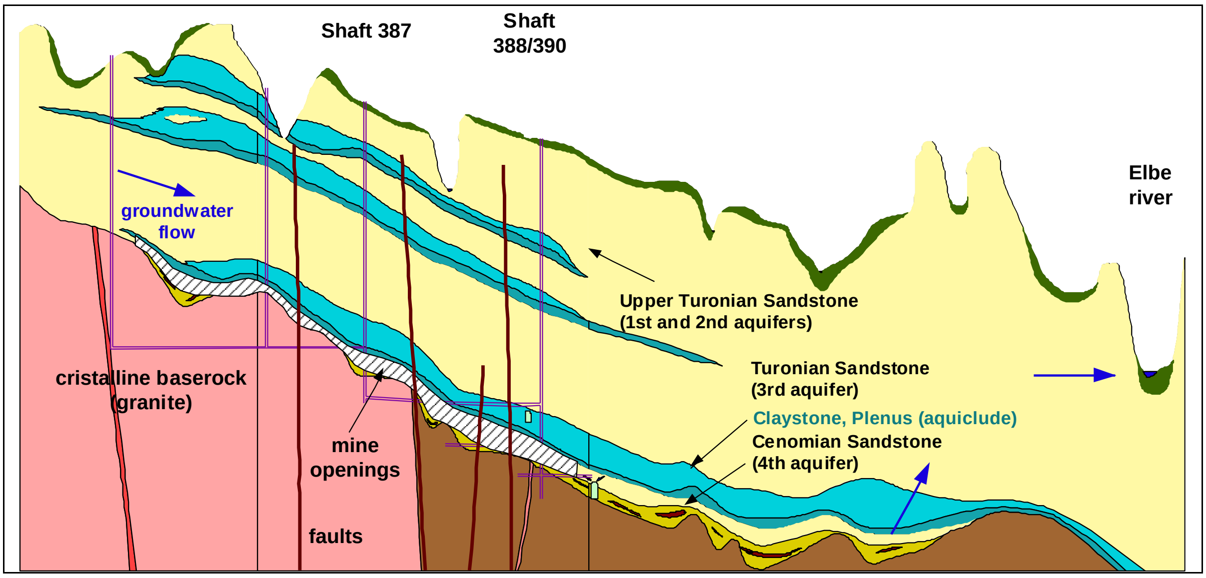

Fig. 1 Schematic Cross Section of the Königstein mine

Predictions of the development of the mine water geochemistry as the source term for the contaminant release into the surrounding aquifers as well as estimations of the spread of contaminants in the aquifers are preconditions for planning and licensing the remediation activity.

2 GENERAL MODELLING APPROACH

The general modelling approach is based on an understanding of hydrogeological and geochemical conditions in the mine and the surrounding aquifers. This includes the necessary reasoning for the choice of the modelled area and relevant boundary conditions, summary of the range of values of relevant model parameters and necessary assumptions as well as the identification of relevant processes which have to be taken into account for a proper model description of the natural conditions. The expected change of parameters and boundary conditions for the future modelled area has to be summarized. These aspects are included in the Conceptual Site Model (below) which is the conceptual basis for the modelling work and has to be continuously further developed based on the gained additional knowledge.

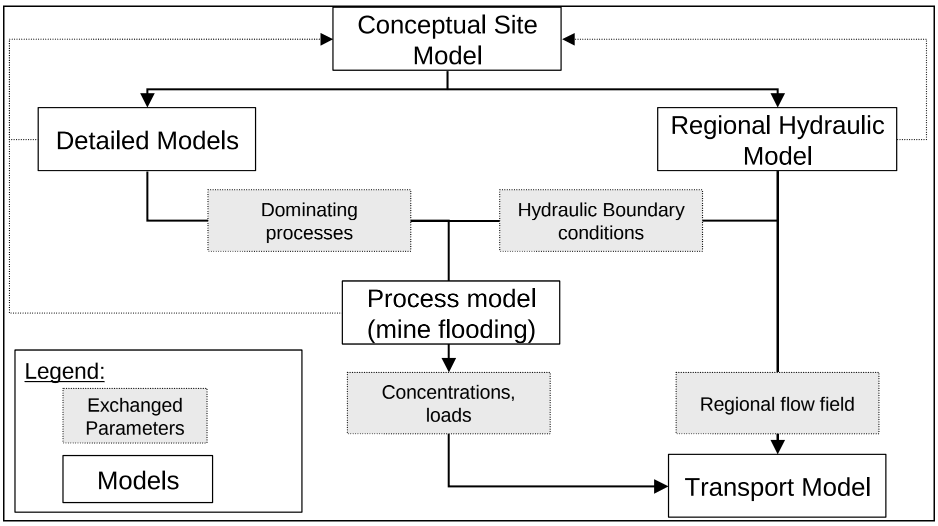

Fig. 2 Flow Chart of the modelling approach for the Königstein mine flooding

For the identification of relevant processes and parameters a wide range of detailed models is set up. They consider various hydrogeological and geochemical aspects as well as different temporal and spatial scales. There were different lab experiments conducted in preparation of the mine flooding at the Königstein site. These tests were reproduced by model calculations.

In the Königstein case a long-term release of contaminants from sandstone blocks is considered to be determined by density driven flow. To identify relevant process parameters a lab experiment on a sandstone block was conducted. This experiment was modelled prior and after the lab measurements.

Fig. 3 Lab experiment on a sandstone block of density driven flow

3 REGIONAL GROUNDWATER FLOW MODEL

Modelling regional hydraulic conditions requires the selection of an appropriate model code depending on local hydrogeological conditions. In regional flow fields where underground mines interact with overlaying aquifers several free groundwater surfaces exist. The representation of these free surfaces in the hydraulic model influences the model water balance.

Compared to a natural aquifer system underground mines are characterised by

- a preferential hydraulic connection through the system of mine workings, resulting in
- a nearly equal water table in the mine or at least within mine fields and,
- different storage behaviour of open mine workings and the bedrock.

The flooding of an underground mine is a superposition of an immediate storage in the flooded mine openings and a retarded storage in the blocks of bedrock influencing the duration and characteristics of the mine flooding. Unified water table of a widespread mine or mine field influences the regional flow regime. In one part the mine will act as a sink while in the other it behaves as a source, with all in- and outflows eventually including also that the pumping and recharge are balanced in steady state conditions. The interaction of the mine with the surrounding aquifer has to be implemented in a physically correct way.

The representation of these characteristics in a commercial ground water flow is difficult and requires a number of workarounds. For Königstein the commercially available model package SPRING® was therefore extended with a special mine boundary condition developed for this mine site.

The basic idea is to implement a separate water balance calculation for all finite element knots representing the mine or separate mine fields in the regional flow model within each time step of the model run. Depending on the mine water level and the geodetic height the finite element knot represents either a seepage ($h_{\text{Mine water level}} < h_z$) or as a potential head ($h_{\text{Mine water level}} >= h_z$) boundary condition. For each modelled time step the boundary conditions of the mine knots is determined depending on the mine water level of the previous time step. For the model calculations these temporary boundary conditions are used. By calculating the in- and outflow balance of all mine knots the water volume stored or released can be calculated. Using the storage characteristics of the water level/ flooded volume relationship (Fig.4) of the mine the new mine water level is calculated.

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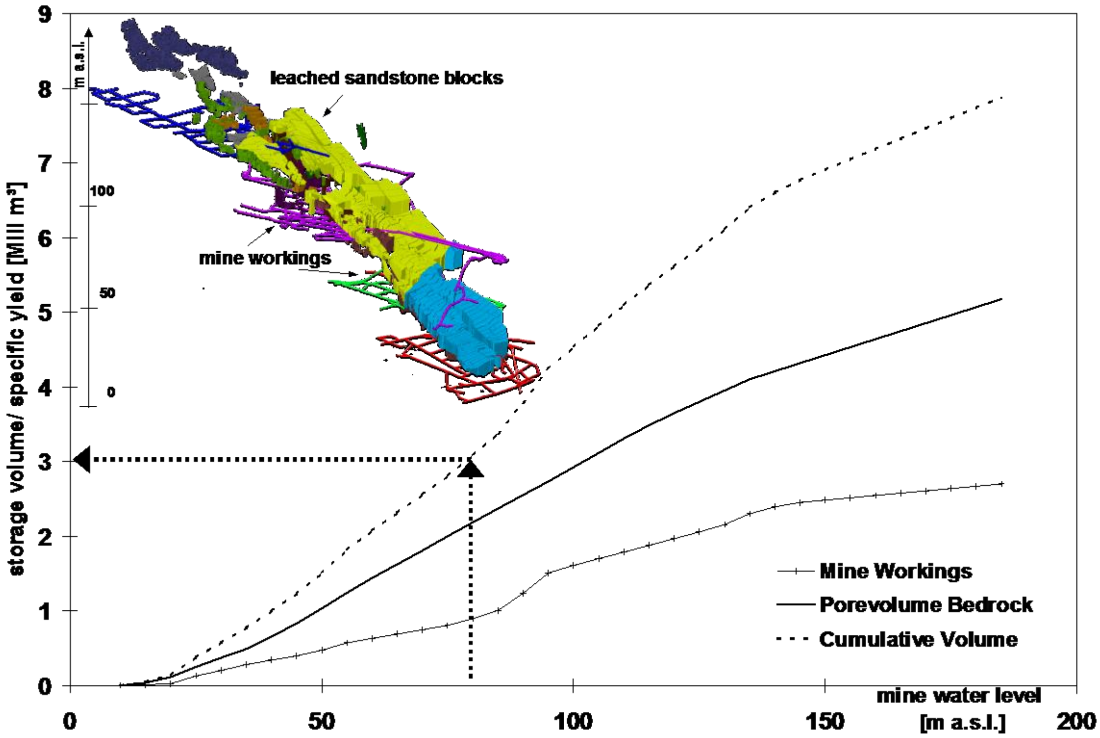

Fig. 4 Storage characteristics of the Königstein mine based on mine surveying and the results of the flooding experiments and the determination of the potential head depending on the water storage in the mine (picture inside: 3D-visualisation of the Königstein mine).

This procedure ensures a high numerical stability of the flow model with an appropriate representation of the influence of flooded and unflooded parts of the mine in the regional groundwater flow field. Furthermore, the necessary discretisation effort to describe the mine or mining fields is reduced. The development of the mine water level as well as the changes in regional flow conditions can be predicted in one model run for the dewatering and flooding of the underground mine. It is assured by this approach that the potential head does not fall below the mine bottom. A coherent water balance of the whole and/or of compartments of the underground mine is calculated for each time step based on the water storage characteristics of the underground mine determined by mine surveying. The approach allows a flexible modelling of changing water pumping or outflow regimes of the flooded mine.

4 MODELLING THE CONTAMINANT RELEASE

For modelling the contaminant release a box model was set up describing the geochemical and generalised hydraulic conditions within the mine. The boxes have an internal structure to represent the open mine workings and the matrix of the bedrock (pore space). Depending on the mine water level saturated and unsaturated parts are distinguished (Fig. 5). The mine openings part and the pore space part are implemented as separate mixing cells.

Each box is characterised by geometric parameters such as

- geodetic height of the bottom,
- total thickness,
- total volume of the open mine working and of the pore space in the bedrock.

The connection between the mine opening and the pore space is characterised by a hydraulic conductance.

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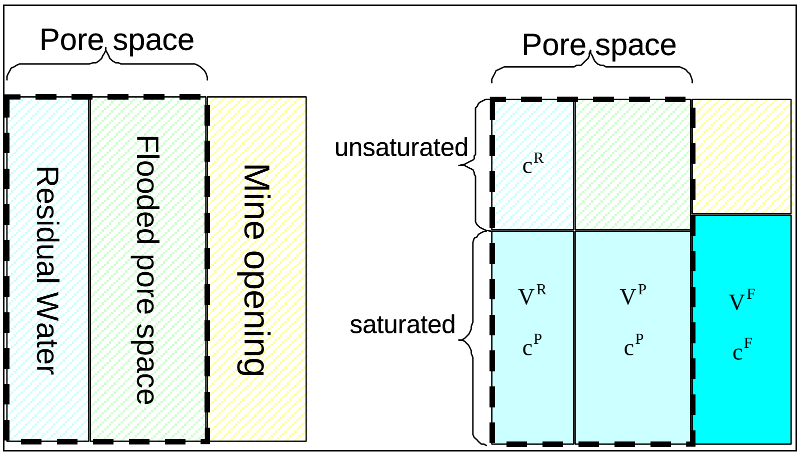

Fig. 5 Concept of the internal structure of boxes

The Königstein mine model includes 17 such boxes. 9 boxes describe the mine workings in the productive sandstone strata with the described characteristics. The other 4 represent the mine base levels. The mine workings at these base levels were used for the material transport and are driven into granodiorite and granite base rocks which is practically impermeable and does not offer a relevant water storage capacity.

The mine openings part of neighbouring boxes is hydraulically connected. The propagation of water inflow through the mine is described by balancing in- and outflows in the different parts of the mine. The hydraulic communication of the boxes with the surrounding aquifer can be defined as time dependent in- or outflow boundary conditions. Within the boxes the exchange of water between the mine opening and the pore space is implemented.

The mass transport between the boxes is implemented as advective transport depending on the hydraulic conditions. Within the boxes the mass transport occurs advectively and by the density driven flow. The transport is based on the differences in density and the hydraulic potential in the mine openings and the matrix part of the box.

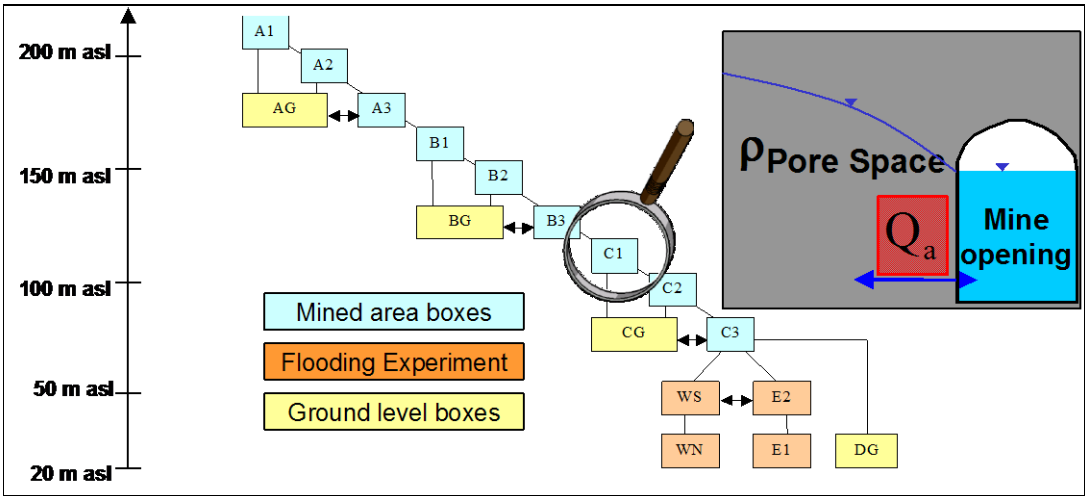

Fig. 6 Representation of the flooded mine in the box model

The hydraulic boundary conditions of water in- and outflow to the mine are defined based on either measurements or the results of the regional flow model. The contaminant release model was calibrated using the measurements of the flooding experiments conducted in the 1990s. The model is continuously validated during the ongoing flooding of the mine allowing parameter adjustments based on the monitoring results. It is used as a tool for the prediction of the expected contaminant release of different flooding scenarios to allow the optimisation of the further flooding process and to gain permission from authorities for the future remediation activities (Fig. 7).

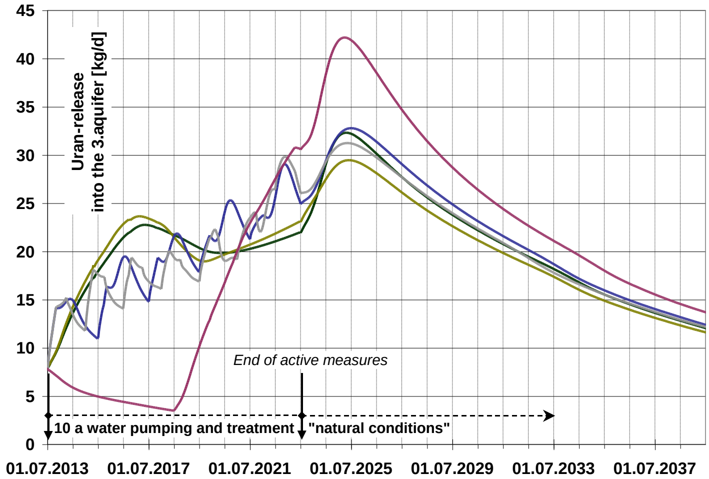

Fig. 7 Prediction of contaminant release (U-load) for different mine flooding scenarios

5 TRANSPORT MODELLING

The predictions of the contaminant transport in the surrounding aquifers are based on the results of the regional hydraulic model and the contaminant release model. Unlike the contaminant release from the mine the relevant geochemical processes and the effective geochemical conditions in the downstream aquifer are just roughly known. It was found by geochemical modelling that small changes in the content of reactive minerals (such as calcite or pyrite) in the aquifer matrix may tremendously influence the propagation of contaminants. There is a limited number of mineral investigations of the aquifer material showing a range of the reactive mineral content of several orders of magnitude. Based on this data any reliable predictions of the contaminant propagation are impossible.
There are 2 possible approaches for the prediction of contaminant propagation, either

- to calculate the spread of contaminants like tracers as a worst-case scenario, or
- to calculate the scenarios with a geochemical model.

Königstein WISMUT follows both approaches. Using the results of the contaminant release model the contaminant spread is predicted using the regional flow model. Thereby the possibly influenced area within the aquifers could be estimated mainly based on the hydraulic conditions (Fig. 8).

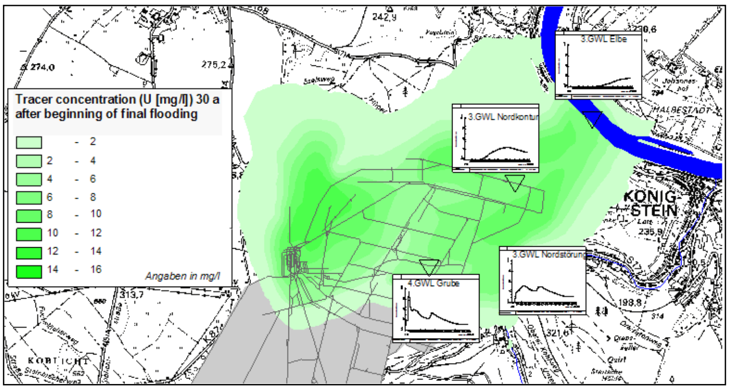

Fig. 8 Prediction of the contaminant spread in the 3rd aquifer for a flooding scenario

In addition a 1D-reactive geochemical model using the transport option of the PHREEQC-code is developed at present. This model is used for process studies to improve the understanding of relevant geochemical processes and to identify sensitive parameters concerning the geochemical composition of the released mine water and the solid phase of the downstream aquifers. The model allows to conduct analyses of various flooding scenarios using the results of the regional hydraulic flow model and the contaminant release model.

6 CONCLUSIONS AND OUTLOOK

The hydraulic and geochemical modelling of contaminant release and its propagation through the downstream aquifer is necessary for planning and optimizing the remediation of uranium mining and milling legacies as well as it is required during the permitting process. For the complex Königstein mine site a modelling concept was developed including hydraulic and geochemical models at various spatial and temporal scales and procedures of consistent coupling of these models.

Based on the experience gained during the modelling work in the past years the following main conclusions for similar modelling tasks could be drawn:

- No commercial models allowing the prediction of both hydraulic and geochemical conditions for different spatial and temporal scales exist. To prepare consistent predictions a set of models has to be used which have to be combined.
- Basis for the modelling of a complex site is a conceptual model reflecting the main processes to be covered, the relevant parameter and boundary conditions. The conceptual understanding of the modelled area and processes should be continuously kept up-to date in an appropriately documented form.
- Geochemical modelling of contaminant release from flooded mines should focus on integral balance volumes instead of a representation of local conditions. The geochemical composition of the solid phase might differ in orders of magnitude. An appropriate scenario analysis allows to improve the understanding of potential effects and helps to identify sensitive parameters which could be in the focus of a more detailed investigation.

At the Königstein site the existing modelling tools will be further validated using the monitoring results of the mine flooding. This will lead to a narrowing of the range of model parameters and thereby increase the quality of predictions. Nevertheless, the main task of the models will remain to support the understanding of potential effects and to allow a qualitative comparison of the effect of different remediation strategies. The inherited uncertainties of the modelling results have always to be taken into account when the environmental impacts of remediation activities are evaluated.

7 ACKNOWLEDGEMENT

The modelling of hydraulic and geochemical processes at the Königstein site is a complex task and requires the input of expertise from various professional fields. This implies the involvement of a great number of experts such as the colleagues from WISMUT and consultants from delta-h GmbH Witten, UIT GmbH Dresden, GFI GmbH Dresden and Prof. van Berk from the Technical University in Clausthal-Zellerfeld who developed and calibrated various models being a fundamental part of the outlined general modelling concept at the Königstein mine site.

RESUMÉ

V letech 1964 – 1990 probíhala na Dole Königstein těžba uranu jak konvenční dobývací metodou, tak i loužením in-situ z pískovcových kolektorů. V důsledku této metody chemické těžby a sekundárního efektu - oxidace pyritu, má pórová voda horninové matrice pH nižší než 2 a vysoké obsahy uranu, železa a síranů. Dalším zdrojem kontaminace důlních vod jsou rozpustné evaporáty, jež jsou vysráženy v otevřených suchých důlních dílech. Tyto se v průběhu zatápění zpětně rozpouštějí a tvoří maximální podíl kontaminační zátěže v počátečních fázích zatápění důlních prostor. Důlní vody z ložiska jsou čerpány prostřednictvím vrtů a vyváděny k přečistění na úpravnu. Cílem sanace dolu je revitalizace hornicky postižené oblasti, tj. obnovení přírodních podmínek proudění a kvality podzemních vod.

Hydraulické a geochemické modelování přestupu a šíření kontaminace podzemní vodou je nutné pro plánování a optimalizaci sanace oblasti a je i legislativně vyžadováno v rámci povolovacích procesů. Pro oblast Dolu Königstein byl vyvinut konceptuální model zahrnující hydraulické a geochemické modelování v různých prostorových a časových měřítcích, jakož i procedury jejich konzistentního propojení.

Na základě zkušeností získaných v průběhu prací na uvedeném projektu v minulých letech je možno prezentovat závěry týkající se podobných úkolů:

- Komerční modely umožňující predikci jak hydraulických, tak geochemických podmínek pro různá prostorová a časová měřítka jako celek neexistují. Provedení konzistentní predikce proto vyžaduje kombinaci řady dílčích modelů.

- Základem modelování takovéhoto komplexního problému je vytvoření koncepčního modelu, jež odráží všechny důležité procesy ke kterým na lokalitě dochází, včetně relevantních parametrů a okrajových podmínek. Konceptuální předpoklady, týkající se modelované oblasti a probíhajících procesů, by měly být kontinuálně aktualizovány a ve vhodné formě dokumentovány.
- Geochemické modelování uvolňování kontaminantů do důlních vod zatopených dolů by se mělo soustředit na režim bilančních objemů jejich zdrojů. Geochemické složení pevné fáze může být variabilní i v rámci několika řádů. Vhodná analýza jednotlivých scénářů umožní zlepšit chápání potenciálních dopadů a pomůže identifikovat citlivé parametry, na něž by se měl soustředit další případný průzkum a výzkum.

Existující simulační nástroje na Dole Königstein jsou zpětně validovány výsledky geochemického monitoringu zatápění dolu. To v konečném důsledku vede k zúžení rozsahu modelových parametrů a ke zvýšení spolehlivostí prediktivních závěrů modelu. Hlavním cílem modelových predikcí zůstává pochopení potenciálních dopadů na hydrosféru životního prostředí a kvalitativní srovnání efektu různých sanačních strategií. Jsou-li hodnoceny environmentální dopady sanačních aktivit je nutné zohlednit i nejistoty spojené s výsledky modelování.

APPENDIX : Presentation **„Flooding of The Königstein Underground Mine Hydraulic and Geochemical Modelling Approach“ *) -** October 2009 in Königstein, Germany

*) Appendix of individual articles has not language correction

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