

MODELLING OF CONTAMINANT RELEASE FROM A URANIUM MINE TAILINGS SITE

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ABSTRACT

Uranium mining and milling continuing from the early 1960's until 1990 close to the town of Seelingstädt in Eastern Germany resulted in 4 tailings impoundments with a total tailings volume of about 105 Mio. m³. Leakage from these tailings impoundments enters the underlying aquifers and is discharged into surface water streams. High concentration of salts, uranium and several heavy metals are released from the tailings. At present the tailings impoundments are reshaped and covered. For the identification of suitable remediation options predictions of the contaminant release for different remediation scenarios have to be made.

A compartment model representing the tailings impoundments and the surrounding aquifers for the calculation of contaminant release and transport was set up using the software GOLDSIM. This compartment model describes the time dependent hydraulic conditions within the tailings and the surrounding aquifers taking into account hydraulic and geotechnical processes influencing the hydraulic properties of the tailings material. A simple geochemical approach taking into account sorption processes as well as retardation by applying a kd-approach was implemented to describe the contaminant release and transport within the hydraulic system. For uranium as the relevant contaminant the simple approach takes into account additional geochemical conditions influencing the mobility. Alternatively the model approach allows to include the results of detailed geochemical modelling of the individual tailings zones which is then used as source term for the modelling of the contaminant transport in the aquifer and to the receiving streams.

The implemented compartment model allows to predict the effect of various remediation scenarios in a fast and traceable way. Furthermore the model can easily be extended by either incorporating additional relevant processes or by results of detailed models reflecting additional local effects.

INTRODUCTION

In 1947, the Soviet occupation forces in Germany established the state-run stockholding company (SAG) Wismut. Run by the Soviet military, the company's sole aim was the exploitation of the East German uranium deposits for the Soviet nuclear program. Founded in 1954, the new bi-national Soviet-German company (SDAG) Wismut continued uranium mining. However, in the wake of the German reunification in 1990, more than 40 years of intensive uranium mining and milling came to an end. Between 1945 and reunification of Germany (1989) more than 231 000 t of U₃O₈ have been produced in Saxony and Thuringia, East Germany [1]. In global terms, this ranks WISMUT in post-war uranium production as number three, after the United States and Canada.

In 1991, the Soviet Union relinquished its shares under the terms of a state treaty. The Federal Republic of Germany took over the stock shares to 100%, and also assumed the responsibility for the remediation of the devastated area. WISMUT was restructured and charged with the decommissioning of mining and milling installations and with remediation of the sites. Following reunification, € 6.6 billion were committed to remediation of the liabilities and Wismut GmbH has been entrusted with the implementation of the task.

WISMUT has responsibility for the rehabilitation of the tailings impoundments at the Crossen and Seelingstädt sites. The tailings ponds at the Seelingstädt site cover an area of 350 ha and contain about 105 Mio m³ of material.

The tailings were discharged into special impoundments as slurry resulting in great volumes of water in addition to the solid residues, which are both radioactively and chemically contaminated. In general under the social and climatic site conditions the dry in-situ stabilisation with partial dewatering of the tailings was identified as the most appropriate

remediation option. The “dry” reclamation strategy was justified by using a probabilistic risk assessment under consideration of the remedial costs, health and environmental benefits as well as socio-economic factors with the aim to develop a site-specific remedial solution sustainable in the long term. This reclamation strategy includes the following steps: (1) Removal, treatment and discharge of supernatant water; (2) Interim covering of exposed tailings areas; (3) Re-shaping of dam and tailing surfaces; (4) Final covering of contoured surfaces; (5) Landscaping and re-vegetation; (6) Collection, treatment and discharge of seepage waters as well as long-term monitoring.

SITE CONDITIONS

At the Seelingstädt remediation site the Trünzig and Culmützsch tailings facilities are situated, both consisting of 2 separate impoundments A and B. The tailings materials of the impoundments had been pumped into the former mine pits Trünzig and Culmützsch where sandstones containing uranium mineralization were mined. The mined out rocks were processed together with uranium ore from the Ronneburg and Aue mining sites at the processing plant in Seelingstädt. Processing residuals were pumped to the tailings ponds. Table 1 shows some typical values of the tailings material deposited in the 4 impoundments.

Tailings impoundment		Culmützsch		Trünzig	
		A	B	A	B
Surface area	ha	159	76	67	48
Volume	Mio m ³	61	24	11	6
Solid mass	Mio t	64	27	13	6
Max. thickness	m	72	63	30	28
Unat in solids	t	4800	2200	1500	700
Ra-226 in solids	10 ¹⁴ Bq	7.9	2.4	1.3	0.5
Unat in pore water	mg/l	0.3 ... 3.9	1.0 ... 16.5	1...19	1...20
Ra-226 in pore water	mBq/l	...5000	...2300	630	N.A.

Table 1 Characterization of tailings material in the modeled impoundments

The tailings ponds are situated in the catchment area of the brooks Culmützsch and Fuchsbach which receive the seepage water from the tailings impoundments which infiltrates below the facilities into the aquifer and is then discharged into the surface streams.

After the end of uranium production in 1990 the deposition of tailings material stopped. In the following years the lakes of supernatant water on top of the tailings impoundments have been withdrawn to achieve the necessary conditions for the start of the remediation work. Temporarily the ponds were used as a collection and storage basins for contaminated seepage waters and surface run-off which had to be treated in a water treatment plant.

For the planning and licensing of the necessary remediation work modelling tools are necessary to predict the development of the seepage water quantity and quality influencing the surrounding aquifers and surface water streams. Main concern of the licensing authorities is focused on the salt load and the discharge of uranium and heavy metals from the tailings impoundments.

GEOCHEMICAL COMPOSITION OF TAILINGS MATERIAL

Processing of uranium ore was done with two different technologies. Depending on the composition of the ore an alkaline or acidic processing technology was applied. Both tailings sites contain two separate ponds which were filled with the remains of either processing technology. The A-ponds contain the tailings material from acidic processing.

The material in the A-ponds has still pyrite concentrations in the range of 2 to 5 mass% while the neutralization potential is limited. The material of the B-ponds has a higher neutralization potential due to the original ore composition and the processing technology. Before the material was discharged into the ponds the solutions were neutralized. Therefore the pH-values of the pore waters mostly are in the neutral range. However, due to the pyrite contents the material in the A-ponds has an acidification potential under oxidizing conditions.

The geochemical environment within the impoundments is highly complex. In particular, it appears that the geochemical trends observed are in part artefacts of the ore beneficiation methodology used over time, rather than being only due to geochemical processes. This complicates or at least adds to the uncertainties of any detailed geochemical modelling significantly, as it is not possible to calibrate the model to past and existing conditions based on geochemical considerations alone. As a result, a simplified approach was applied to model the source term in the impoundments in the site model.

RELEVANT PROCESSES

Due to the extremely low hydraulic conductivity of the slimes, the flow rate through this portion of the tailings can be assumed to be very low. This influences the dewatering capacity of this type of material and therefore the geochemical conditions resulting from saturated conditions in the long term. On the other hand the sandy material deposited close to the discharge points is permeable with oxygen penetration due to connection to the atmosphere. The different hydraulic properties of the tailings materials is reflected in the discretization of the model.

The material in the slime zone is characterized by void ratios well above 2. During and after reshaping and covering work the water content of the material will decrease resulting in a significant consolidation of this type of tailings material. The resulting excess pore water will drain out mainly to the surface and has to be collected. Due to consolidation and the reduction of the void ratio the hydraulic conductivities will change. The hydraulic properties of the slime material depend on time and material load that is a function of the depth below the surface. Based on the expected low hydraulic conductivity of the tailings material and the water budget of the future cover it can

be assumed that the slime tailings will remain saturated over the long-term.

The sand zone is the main seepage path with higher hydraulic conductivities. The water balance of the sand zone mainly influences the quantity of seepage water from the tailings impoundments. Depending on the feeding by infiltration of rain water or supernatant pond water the sand zone stores and releases significant quantities of pore water. Due to the higher hydraulic conductivity the contaminant potential is faster flushed from the sand zone compared to the fine slime zone. Due to the hydraulic characteristics in the sandy material that acts as an aquifer, saturated and unsaturated zones develop. The saturation of the sandy material influences the geochemical conditions with geochemical interaction in pore water between the gaseous, liquid and solid phases. Oxygen diffusion leads to oxidation of pyrite minerals which is the source for acidification and additional salt load. The structure of the tailings is illustrated in a cross section derived from CPT and drillings in Figure 1

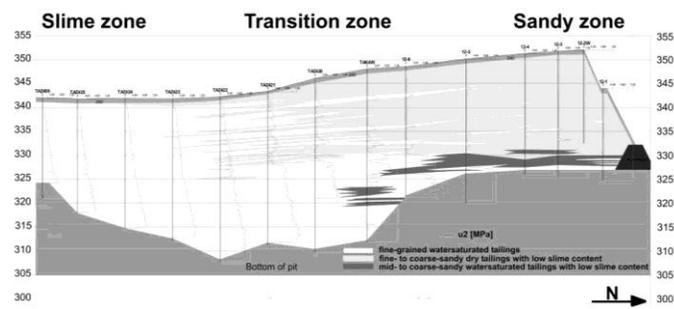


Figure 1 Cross section of the tailings impoundment

The materials of the transition zone combines the properties of the fine-slime and sandy tailings. Due to the geometric conditions horizontal conductivity is significantly higher than vertical. Dewatering of the tailings material will therefore mainly occur over the sandy zone adjacent to the transition zone. Consolidation processes are relevant for the slimy parts of the transition zone.

APPROACH

Purpose of the work is to set up a management model for the whole remediation site with the 4 tailings impoundments and their surroundings as well as other relevant sources of contaminant load, especially different waste rock piles. This model should integrate the available knowledge of the hydraulic, geochemical and geotechnical conditions. Various detailed models exist addressing either individual problems or single impoundments. However, to judge on the effectiveness of single remediation measures their influence on the whole catchment area has to be evaluated by integrating this knowledge into an overall site model.

Special attention is focused on the contaminant discharge through the surface water streams receiving the seepage waters from the impoundments through the underlying aquifers. The receiving streams are the main pathway of contaminant discharge into the wider surroundings. Due to the

hydrogeological conditions the groundwater contamination is mainly limited to the facilities and their close vicinity.

It was therefore decided to implement a hydrogeological geochemical site model as a compartment model which reflects the relevant processes in a simple and traceable way. The compartments of the model are not only boxes, they have an internal substructure to reflect the different types of materials and the different processes that have to be described. This approach allows better judgement on uncertainties which exist in the description of such a complex hydraulic and geochemical system. But the model approach also allows to integrate the results of detailed models as boundary conditions.

The compartment model is implemented in the GoldSim decision support tool. GoldSim is a simulation software solution for dynamically modelling of complex systems in business, engineering and science. This tool was developed for the assessment of final storage facilities of radioactive waste. Because of its flexibility and power, its range of application has been extended, especially to the whole mining sector and to other industries.

The compartments are defined for the relevant units in the modelling area as there are the aquifer underlying the impoundments, different tailings materials and other objects such as waste rock dumps. Furthermore the relevant surface water stream are represented by mixing cells.

The boxes have an internal structure depending on the material they represent. They are characterized by geometric parameters such as volume and geodetic height as well as hydraulic and geochemical properties.

Technological conditions are included in the model such as water treatment, enhancement of dewatering by introduction of wick drains and covering. This especially includes the influences of the technical measures onto the hydraulic and geochemical conditions in the different parts of the system. For example the covering of the tailings forces the consolidation of the slimy parts of the tailings and changes the infiltration and oxygen diffusion. All these effects have to be reflected by the model.

The system of the tailings impoundments is highly dynamic requiring a transient modelling with time dependent boundary conditions and material properties. The change of the parameters is either given from measurement result or is derived from detailed modelling results such as geotechnical models in case of consolidation. Additionally storage effects play a significant role in the system.

MODEL DESCRIPTION

The compartments representing the tailings material are divided into subcompartments according to the 3 different materials. This zonation of the tailings material was based on grain size distribution and the results of CPT-measurements resulting in the geometric characterization of the 3 different material zones. Each of the 4 tailings impoundments was divided into 2 to 4 compartments which include the subcompartments for modelling of the fine-slime, sandy and

transition materials. These zones have different hydraulic geotechnical and geochemical behavior with relevance for the prediction of contaminant release. The internal structure of one of these compartments is shown in Figure 2.

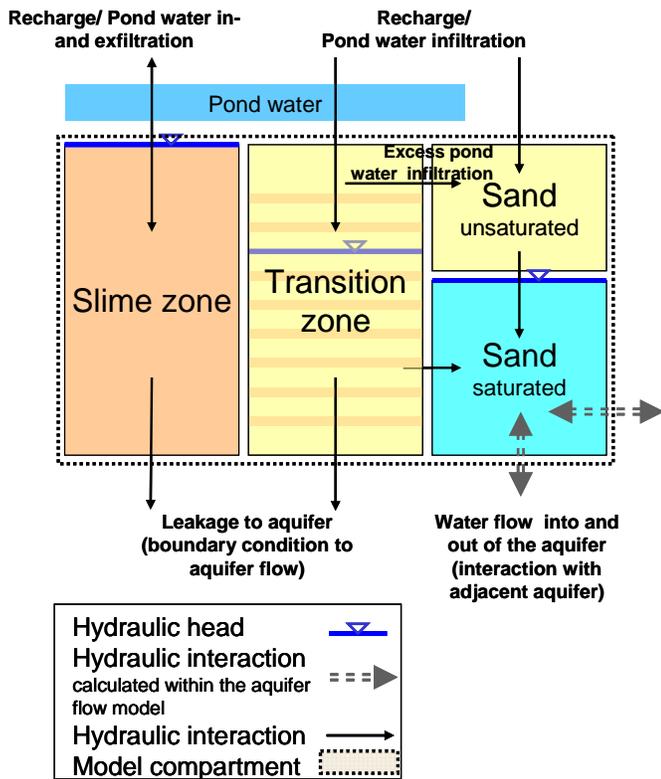


Figure 2 Schematic illustration of the internal structure of a single tailings compartment.

For other objects relevant for hydraulic conditions and contaminant release at this site such as waste rock piles or dams boxes are defined. Based on the groundwater flow conditions and the geometries of the object and tailings boxes the compartments representing the underlying aquifer are distinguished. The model consists of 12 tailing compartments (subdivided into subcompartments), 11 compartments representing waste rock piles or dams, 33 aquifer compartments and 10 mixing cells representing surface water streams.

While the tailings and the waste rock piles are contained in a so called object layer, the groundwater system is contained in a separate groundwater layer. These compartments of these two layers are illustrated in Figure 3.

Groundwater - layer

Object - layer

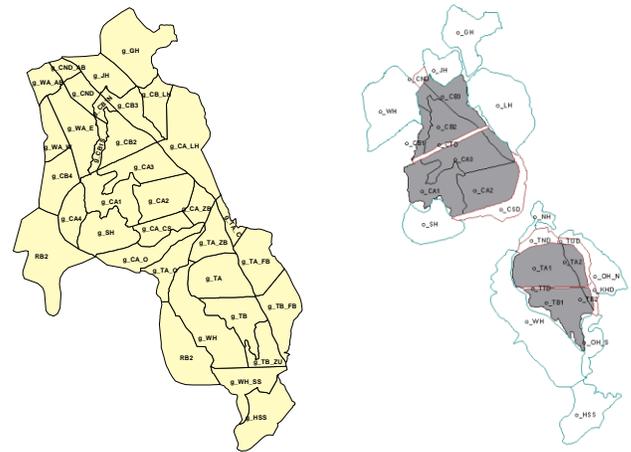


Figure 3 Illustration of the compartments of the groundwater and the object layer

As boundary conditions have been included leakage boundaries representing groundwater discharges into the receiving streams, water pumping from wells within and around the tailings impoundments, hydraulic heads of the supernatant pond water on the impoundments and the average groundwater recharge.

There is a significant interaction between the ponds of supernatant water and the deposited tailings materials. As long as the technological water is on top of the tailings it influences the infiltration into the material, especially into the sandy and transition zone, and as a result the leaching of contaminants from the impoundments. The ponds of water are fed by technological water from the site water management by using them temporarily as storage reservoirs for the water treatment facility, rainfall and excess pore water which is drained from the tailings due to consolidation processes.

Apart from water in the ponds on top of the impoundments rainfall and runoff also seeps into the impoundments contributing to the flushing of the pore water and release of contaminants.

A simple hydraulic model is used to define the water balance within the modelled system including the quantity of water flow between the compartments. The model is based on Darcy's law with average hydraulic heads for each compartment as well as conductance values. Adjacent compartments are connected to each other. In the tailings compartments the sandy zone is directly connected to the groundwater compartment. The seepage from fine slime and transition zone also depends on the level of the groundwater and is included as additional boundary conditions. The hydraulic conditions in the transition and fine slime zone are calculated separately.

The hydraulic model was calibrated based on the historic measurement data of water tables as well as seepage and discharge rates.

The geochemical conditions in the Culmützsch and Trünzig impoundments have been modelled in a similar manner. The A and B impoundments have significantly different geochemical conditions due to the processing technologies used which is reflected in the model by different parameterization. Nevertheless the conceptual model for the facilities is the same.

The geochemical conditions are described separately for the sand, transition and fine slime zone. While the sand and transition zone was subdivided in the unsaturated upper and the saturated lower part for the fine slime only saturated conditions have been assumed. Because of changing water tables the volume of the saturated and unsaturated part is time dependent. The development depends from the boundary conditions (water extraction, cover, etc.) and the development of the groundwater system. This requires to account for changes in the mass balance of each part due to the change of water table.

The geochemical conditions of the tailings material were determined by different sampling campaigns where the composition of the solid and liquid phase have been analyzed. These results are the basis for the definition of the contaminant source term of the impoundments. For the simple approach of the site model two basic concepts of contaminant release were defined. Either the release is solubility controlled or adsorption (Kd) controlled. According to the solubility control model, dissolved concentrations are governed through dissolution or precipitation of mineral phases. In the Kd controlled model the adsorption-desorption ratio is governed by the dissolved concentrations. In both cases, as an initial condition the total mass of each contaminant is applied to the mixing cell based on the current observed dissolved and solids concentration in the slimes. For both cases the observed conditions are seen as initial condition to define the ratio between the contaminants in the solid and the fluid phase.

In the unsaturated zone mass budgets are calculated for pyrite oxidation and the connected neutralization reactions. As long as sufficient neutralization potential is available there are no changes of the pH. In case of changing pH-value the parameters for the solubility or the adsorption coefficient are changed. Two pH-states are considered in the model: a neutral pH and a low pH. Using the analysis results from the sampling campaigns the coefficients for the 2 approaches were determined. Based on geochemical modelling using PHREEQC it was determined that the dissolved concentrations of SO₄, Ca and Mg are controlled by mineral dissolution. Therefore for these species only solubility control is considered. Chloride is treated as tracer without any additional source in the solid phase.

The evolution of the pond water composition was implemented as a chemical boundary condition based on measured values. Flows out of the ponds into the tailings are computed dynamically by the model. The model also takes care of the elimination of the ponds of supernatant water. Therefore predictive simulations do not need to include mass input from the ponds.

Beside the simplified description of the geochemical conditions inside the tailings impoundments, the results of

external geochemical models for the different tailings impoundments have been integrated. The use of either the simplified model for the interior of the tailings or the results of the external model is managed by means of a flag.

The general purpose of the model is the evaluation of different technical measures in regard to the reduction of the environmental impacts. Therefore the system is modelled over a time period of up to 100 years. To ensure the toughness of the model, in front of the prognosis, a history matching was performed. This included the changes of the hydraulic and geochemical system from the mid sixties until today. The approach is confirmed by comparison of modelled results for the different compartments with observations. Because of the high number of existing groundwater observation wells, the concentration values from all wells of each of the compartments have been averaged. Figure 4 shows the modelled concentrations of Sulphate and Chloride for one groundwater compartment in comparison with the averaged observed values for the period from 1994 till 2005.

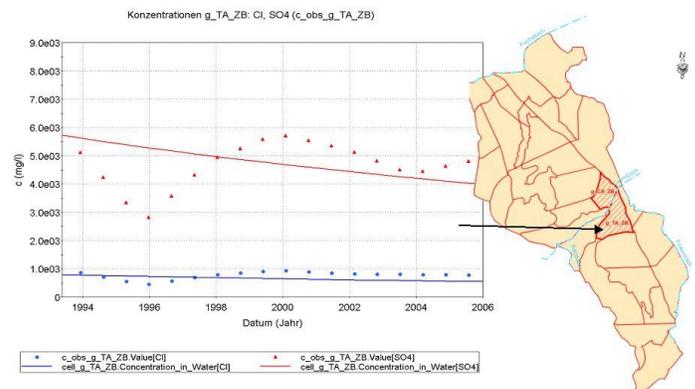


Figure 4 Illustration of the compartments of the groundwater and the object layer

RESULTS

Using this compartment model approach, there was implemented a site model comprising all processes relevant for the water pathway. It was demonstrated, that the model is able to represent the time dependent average values of contaminant releases measured in the past and at present in the surface stream and the average concentrations in the drainage systems and in groundwater. Additionally the development of the average water table heights in the boxes correspond to average values of observations in the respective area.

The approach demonstrated, that a complex site with a variety of contaminant sources can be represented by a compartment model approach integrating the results of different detail models and knowledge about the site.

Because of the overall model structure and the power of the GoldSim simulation tool, the model is very flexible in further adaptations of the parameters and even in the integration of additional processes.

CONCLUSIONS AND DISCUSSION

The conducted work demonstrated, that the applied system modelling approach using a compartment model with an internal substructure of the compartments is very flexible and powerful. Because of this and based on our experience with complex, three dimensional geochemical models that have been developed for single tailings impoundments, we recommend the use of such a compartment model approach based on a fairly rough spatial discretization. Detailed geochemical models should be used to analyze the geochemical processes and to provide inputs for different scenarios. This stepwise approach significantly increases the flexibility and allows to identify the uncertainties of the system.

The major reasons are, tha

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