3D MODELING OF BRINE FLOW - A CASE STUDY FOR A FLOODED SALT MINE

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ABSTRACT

An abandoned and flooded historical salt mine located in Stassfurt (Germany) is studied within a joint research project. The objective of this project is to gain a better understanding of the dynamics of naturally or actively flooded salt mines. Within this survey the stability of the salt mine and the surrounding caprocks is studied. One task within this research framework is the computation of different density-dependent 3D groundwater transport models. Aim of these models is to improve the understanding of the impact of different remedial engineering solutions. For instance, it is studied which amount of salt will be dissolved due to pumping activities. Subsequently, the related potential of subsidence effects is assessed.

A further challenge is the analysis of effects of the underground cavities on the groundwater and mass-transport dynamics. Detailed geometry of the mine workings is included in 3D model schematizations. Chemical reaction kinetics is also considered, where NaCl and $MgCl_2$ are the dominant salt species. Precipitation and dissolution are controlled by the amount of available $MgCl_2$. The consideration of these different salt types can be of importance as they possess different specific densities. Furthermore, permeability and porosity are also affected by precipitation and dissolution. It is shown that the impact of these different chemical and physical relations may have a relevant impact on the modeling result.

The presented work is currently still in progress. However, the availability of 3D numerical models provides many advantages. Despite all limitations these models can serve as effective analysis tools to improve the understanding of the relevant processes.

1. INTRODUCTION

In Stassfurt, Eastern Germany, a large abandoned potassium mine is located. The mine was opened during the 19th century and was one of the first subsurface potassium mines in the world (Stassfurt is the 'locus typicus' for one of the Zechstein salinar series). The mine below the town center located at the southern slope was closed down in 1920 and was completely flooded very soon afterwards. Underneath the town center the largest earth fall occurred at the beginning of the 20th century. It caused a 40 m deep subsidence with a diameter of 140 m. Due to this subsidence more than 850 buildings had to be demolished since 1960. As large areas of the town fell below the groundwater level extensive pumping activities became necessary to reduce the groundwater table in the city.

Due to the continuous risk of earth falls a joint research project has been initiated to serve as a basis for decision-making and sustainable remedial solutions. As already shown in a previous assessment (Maas, 2001) the existence of cavities and the continuous leaching of salt structures represent the main risk factors.

To get more insight into the ongoing subsurface processes, which are still not completely understood, numerical flow and transport modeling is highly required. In the present study the finite-element simulator FEFLOW (Diersch, 2005, Trefry & Muffels, 2007) is used. The modeling work has been scheduled as follows: First, prototypical studies are performed along selected 2D vertical cross-sectional models to obtain basic information on principal relationships which is required to create more complex modeling approaches. Secondly, a detailed 3D flow model is set up and calibrated. Thirdly, a complete mass transport model is set up. Additionally, in the 3D finite element models the geometry of the mine workings is reproduced in detail. Finally, the 3D model is combined with a heat transport analysis to indicate preferential flow movement in the mining area based on measured temperatures.

2. COUPLED MODELING OF DENSITY-DEPENDENT FLOW AND MASS TRANSPORT

The simulation of mass transport within a porous medium requires the solution of a set of balance equations. For the present study free-surface (phreatic) conditions have to be considered.

The governing equation for flow is given by (e.g., Diersch, 2005)

$$S_0 \cdot \frac{\partial h}{\partial t} = \nabla \cdot \left(\mathbf{K} \cdot \left(\nabla h + \chi \mathbf{e}\right)\right) + Q \qquad (1)$$

where S_0 is the specific storage due to fluid and medium compressibility (m^{-1}), h is the hydraulic head (m), t is time (s), χ is the buoyancy coefficient (/) and **e** is the gravitational unit vector (/). Q corresponds to sources and sinks (s^{-1}).

K represents the tensor of hydraulic conductivity ($m\ s^{-1}$), defined as

$$\mathbf{K} = \frac{\mathbf{k}\rho_f g}{\mu_f} \quad (2)$$

where **k** is the permeability tensor (m^2), ρ_f is the freshwater fluid density ($kg\ m^{-3}$), g is the gravitational acceleration ($m\ s^{-2}$) and μ_f is the dynamic fluid viscosity ($kg\ m^{-1}\ s^{-1}$).

The Darcy velocity **q** ($m\ s^{-1}$) is given by

$$\mathbf{q} = -\mathbf{K} \cdot (\nabla h + \chi \mathbf{e}) \quad (3)$$

The mass conservation of the kth chemical species including convection and hydrodynamic dispersion reads

$$\frac{\partial C_k}{\partial t} = \nabla \cdot \left(\mathbf{D} \cdot \nabla C_k\right) - \mathbf{q} \cdot \nabla C_k + R_k \quad (4)$$

where C_k is the concentration of species k ($kg\ m^{-3}$) and R_k is a general reaction term. **D** is the tensor of hydrodynamic dispersion given as

$$\mathbf{D} = \left(\varepsilon D_d + \beta_T |\mathbf{q}|\right)\mathbf{I} + \left(\beta_L - \beta_T\right)\frac{\mathbf{q} \otimes \mathbf{q}}{|\mathbf{q}|} \quad (5)$$

Furthermore, ε is porosity (-), D_d is the molecular diffusion coefficient, β_L and β_T are longitudinal and transverse dispersivities, respectively, **I** is the unit tensor.

Density dependence is taken into account by a normalized ratio of the maximum to the minimum density of the fluid. This ratio is used for the above introduced buoyancy coefficient. For details see Diersch & Kolditz (2002).

3. 2D MODEL SETUP

Three 2D vertical models are analyzed (cf. Figure 4). However, due to their similarity only the cross section P113 (see Figure 1) will be discussed in the following. P113 represents a typical cross section through the central part of the salt dome. The different geological units and their properties are listed in Table 1.

Table 1. Geological units and associated physical properties

ID	Rock type	Porosity ε (/)	Hydraulic conductivity K ($m\ s^{-1}$)
1	Quaternary	0.2	5E-05
2	Lower Triassic	0.08	1E-07
3	Caprock	0.05	5E-06
4	Halite (Aller)	0.01	1E-10
5	Red salt-clay	0.05	1E-08
6	Halite (Leine)	0.01	1E-10
7	Anhydrite	0.05	5E-06
8	Leached Anhydrite	0.1	1E-05
9	Sylvite	0.01	1E-08
10	Leached Sylvite	0.1	1E-05
11	Halite (Stassfurt)	0.01	1E-10

The maximum salt concentration is 314 $g\ l^{-1}$ (assigned as 1st kind boundary condition to all salt units) leading to a buoyancy coefficient χ of 0.2. Recharge at the surface is set to $2.466 \cdot 10^{-4}\ m\ d^{-1}$. The computation is performed using FEFLOW's automatic time stepping procedure (forward/backward Euler predictor-corrector scheme) and is completely coupled by density. Different scenarios are simulated: with and without pumping (cf. Figure 2) as well as with and without an additional inflow at the deeper part of the Triassic at the left boundary. All scenarios are computed for 200 years, starting from a quasi steady-state initial condition. The results are exemplified in Figure 3.

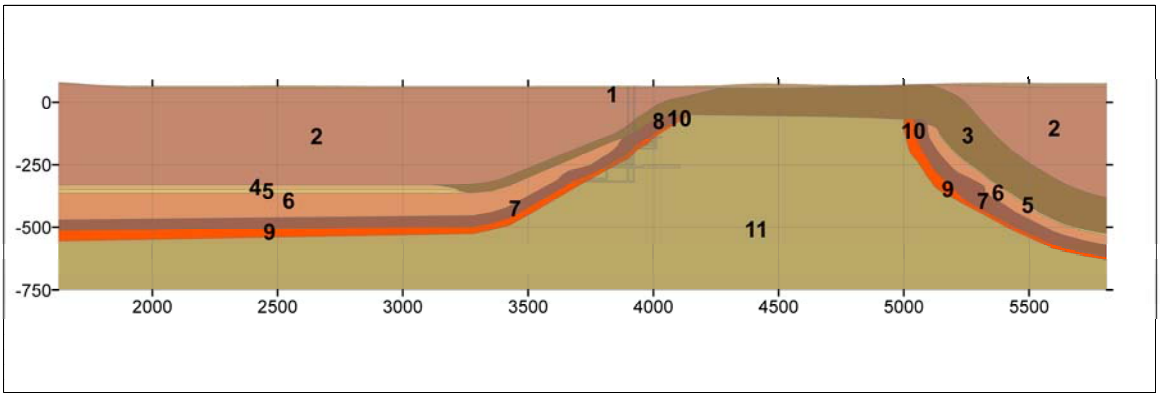


Figure 1. Cross section P113 (cf. Figure 4). Geologic structure of the 2D model (numbered geological units are listed in Table 1) and mine workings.

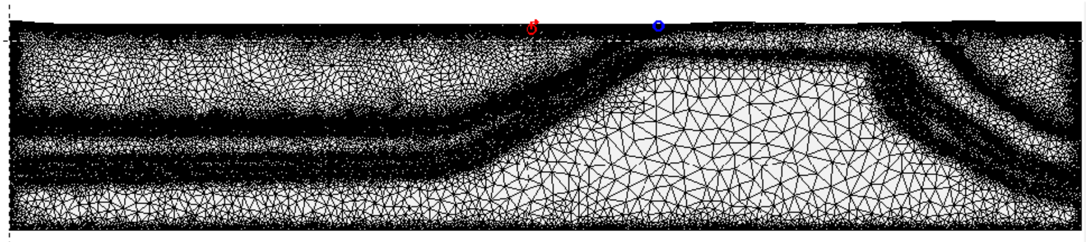


Figure 2. The finite element mesh of the cross section shown in Figure 1with location of boundary conditions (red symbol indicates pumping well, blue symbol indicates crossing Bode river).

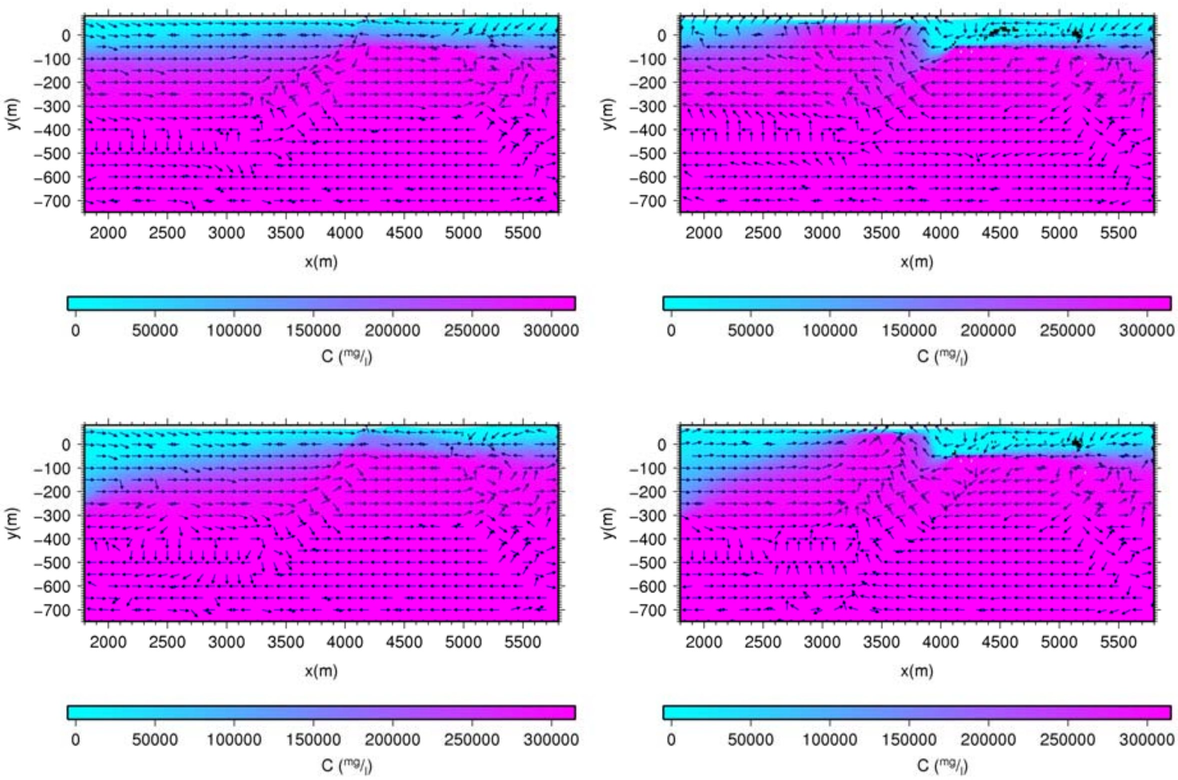


Figure 3. Different scenarios simulated for cross section P113. Depicted are the salt concentration and vectors of flow. Top/left: without any in/outflow except of the Bode river; top/right: with pumping (located in the middle of the cross-section); bottom/left: with an inflow from the deeper subsurface (Buntsandstein, left boundary); bottom/right: with pumping plus inflow from the Buntsandstein.

The results shown in Figure 3 indicate that the river Bode has a significant impact on the mass distribution due to the associated relaxation. Additionally, the pumping shows an even stronger effect. The high permeable Triassic units have a negligible impact as the inflow from the deeper subsurface has only slightly effects the mass distribution.

The 2D modeling provides important information on necessary mesh resolution. The effect of different settings, such as different hydraulic conductivities and different types of boundary conditions on the achieved results can easily and quickly be investigated. However, those 2D models are rather inappropriate for gaining quantitative information about the mining area.

4. 3D MODEL

After completion of the 2D model studies a regional 3D model is set up. Necessary data are, similar to the 2D case, the geometry of the hydrogeological units with related conductivities, initial hydraulic head, groundwater recharge and boundary conditions (such as Bode river and related ditches, pumping wells and no-flow boundaries).

The model domain covering an area of about 88.5 km² is firstly discretized by a finite element mesh consisting of 734,880 triangular prismatic elements and 393,456 nodes in total. The element sizes vary between 3 m – 400 m, with a finer resolution of 5 m – 25 m being chosen for the mining area (see Figure 4).

The 3D groundwater model contains 15 primary model layers, accounting for the relevant hydrogeological features of the aquifer system (ref. Table 1 and Figure 5a). The boundary conditions considered in the model are (Figure 5b)

1) 3rd kind boundary conditions describing the interaction of groundwater and relevant Bode river and related ditches in the model area;
2) well boundary conditions representing pumping for lowering of the groundwater table in the model domain;
3) no-flow and flux boundary conditions describing in- and/or outflow through the borders of the model domain.

During calibration the spatial distribution of the hydraulic conductivity and the leakage rates for bed deposits of the river Bode with connected ditches have been found to be the most critical parameters. The model calibration is performed using several head measurements with a lot of them being measured at newly created monitoring stations.

The calibrated flow model is subsequently extended to a variable-density 3D solute transport model. The objective is to reproduce field observations of salinity and to improve the understanding of causal relations in the historical flooding processes and consequences of remedial engineering for better strategies in future developments.

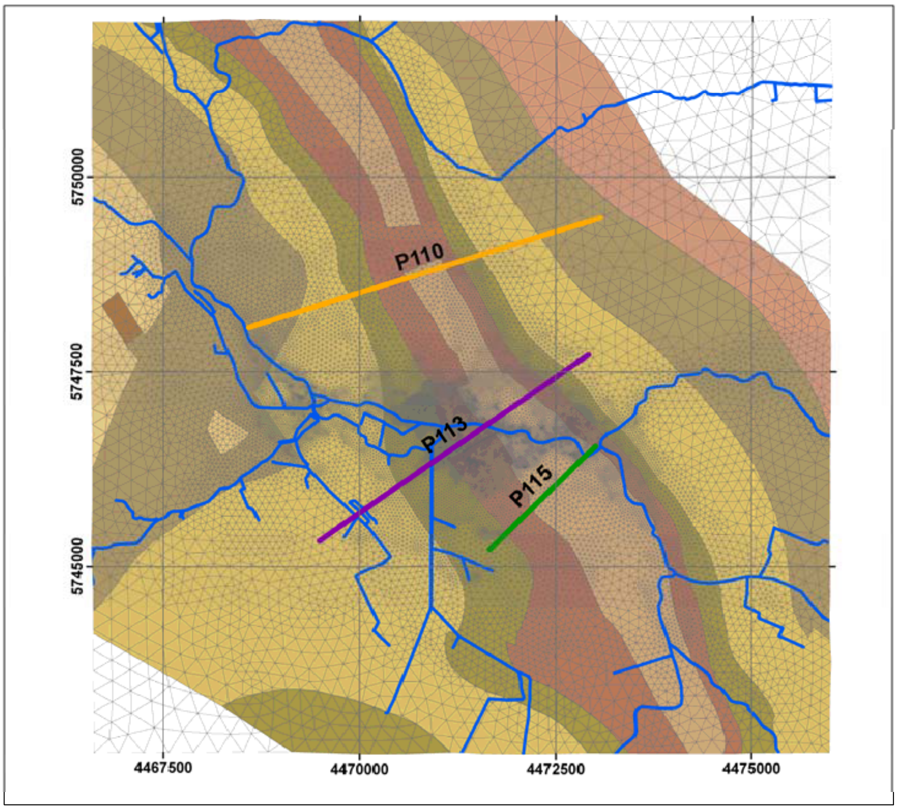
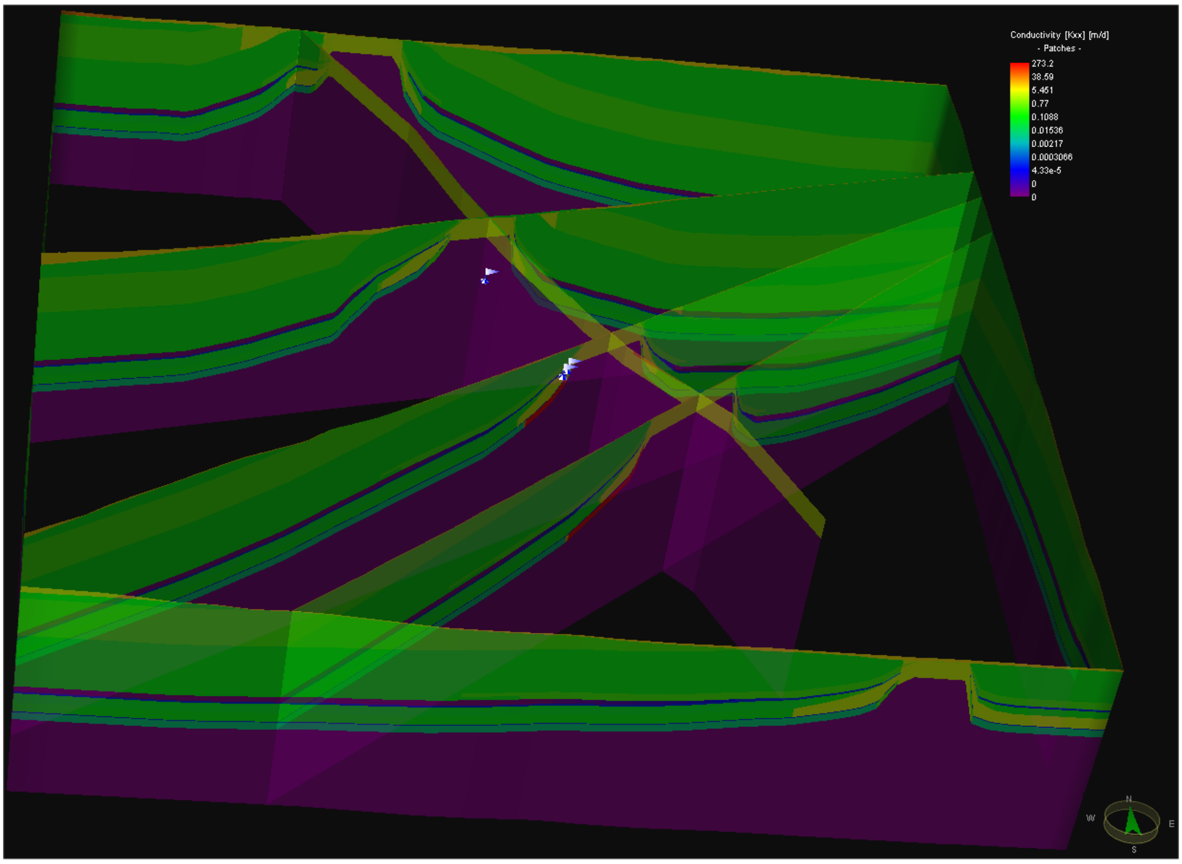
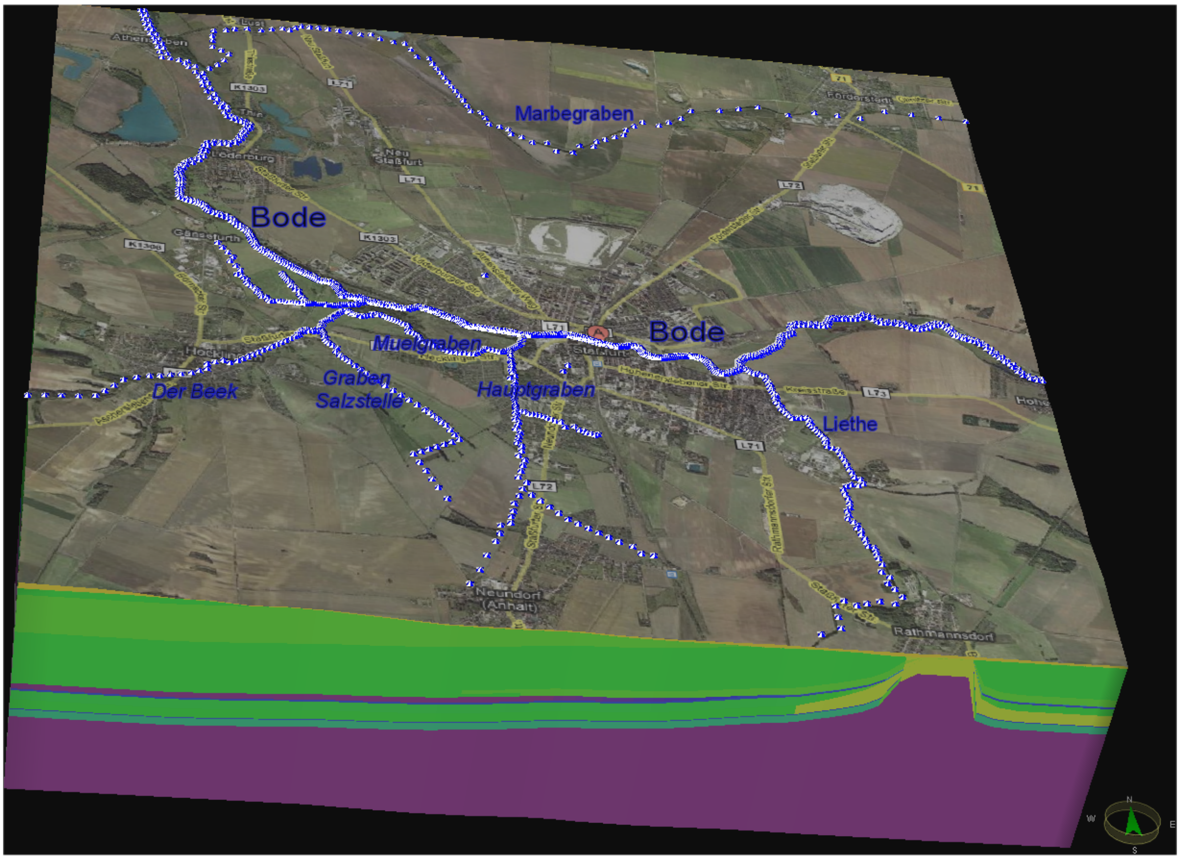


Figure 4. 3D model showing the finite element mesh, the geology (depicted in colored areas), the Bode river and ditches (presented by blue lines) and the computed cross sections (P110, P113, P115). The coordinates are given for the Gauss-Krüger system (measured in meters).



a) Fence view of the 3D groundwater model.



b) Relevant Bode river and related ditches acting as boundary conditions.

Figure 5 **Overview of the 3D groundwater flow and transport model.**

5. MODELING OF TWO SALT SPECIES

Chemical reactions are studied for the dominant salt species NaCl and $MgCl_2$. It is assumed that precipitation and dissolution are controlled by the amount of available $MgCl_2$. The precipitation of NaCl species is described via linear approximation. In addition, a mixed bulk density is computed. The change of permeability and porosity due to precipitation and dissolution is considered by reducing the available pore-space according to the amount of precipitated NaCl and by reducing the permeability according to a fractal relationship between porosity and permeability (see Pape et al., 2005). The reaction kinetics are modeled on the basis of FEFLOW's formula editor. The modification of the hydraulic conductivities is performed by using a specific C++ code developed with FEFLOW's open programming interface IFM. Preliminary results show that these chemical processes may lead to the development of very low permeable or even impermeable crust structures at the salt leaching zones. Further studies are currently performed.

6. OUTLOOK

Inclusion of the Mine Workings

Today, the structure of mine workings appears highly irregular and often departs from previous situations when mine was developed and conducted. Some areas have been filled, others have uncontrolledly subsided or are still open and stable. Currently, a model is being built, were all known mine workings are included. In Figure 6 an example of such a FEFLOW model is displayed (taken from Renz et al., 2009). While the movement of water within the porous matrix can be calculated based on the Darcy law, the flow in the open mining structures is a free-fluid movement, which has to be modeled via a Manning-Strickler law for turbulent flow and a Hagen-Poiseuille law for laminar flow. These flow specifications are accomplished by using a numerical technique termed as Discrete Feature Elements which is also available in FEFLOW (see Diersch, 2005).

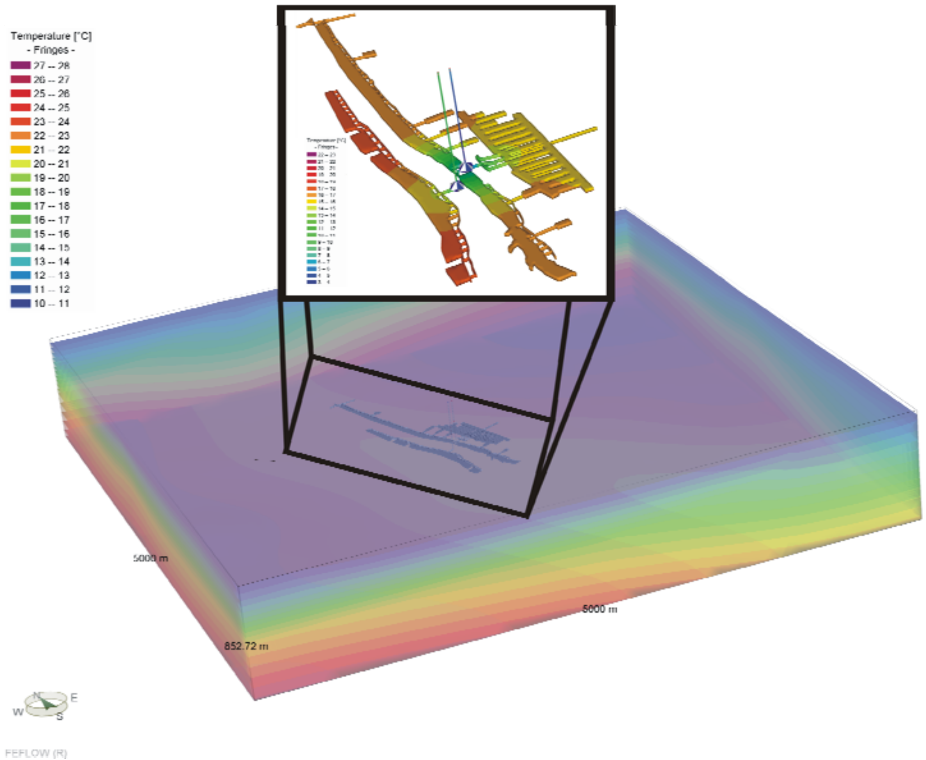


Figure 6. 3D model showing a computed temperature distribution. In the magnified image the temperature in mine workings is displayed (from Renz et al., 2009).

As an additional investigation the complete 3D model is combined with a heat transport analysis. Differences between computed and measured temperatures in the underground will indicate regions where advective (convective) heat transport may occur and where consequently the subsurface can be highly permeable (e.g., Anderson, 2005).

7. CONCLUSIONS

The presented work is currently still in progress, the results should therefore be understood as preliminary. In modeling flooded salt mines as exemplified for the Stassfurt mine site different strategies and approaches have shown suitable and powerful. The availability of 3D numerical models provides many advantages. Despite all shortcomings due to the limited knowledge of the subsurface they serve as effective analysis tools to understand the historical and future processes in a better way and work as a basis for decision making and sustainable remedial engineering strategies.

8. ACKNOWLEDGEMENTS

We thank two anonymous reviewers who helped to improve this paper.

This work is performed within the project ‘Dynamics of drowned or flooded salt mines and their overburden level’, which was funded by the Federal Ministry of Education and Research Germany (BMBF) under contract 02 C 1516. The project will be finished in June 2010.

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