3D Modeling of Saline Groundwater Flow and Transport in a Flooded Salt Mine, Staßfurt/Germany

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Abstract The abandoned and flooded historical deep salt mine Staßfurt/Germany has been extensively studied within a joint research project. The salt mine causes serious uncontrolled salt leaching and mass displacement effects in the underground which have led to significant subsidence at regional scale. There is a potential danger for the city of Staßfurt due to collapsing of mining areas and further large subsidence. Main objectives are the assessment of the stability of the salt mine with the surrounding cap rocks and the potential of subsidence due to salt leaching processes. For better controlling (minimizing) the salt leaching a comprehensive modeling of the 3D variable density flow dynamics at both large scale and local scale of the site is required. The impact of different engineering solutions and appropriate remedial strategies (e.g., pumping schemes) on the subsurface spatio-temporal distribution of salinity is of specific concern. The coupled variable density flow and transport simulations are performed by the finite-element simulator FEFLOW, which features capabilities to include both porous media (Darcy-type) flow computations and lower-dimensional discrete elements for laminar or turbulent flow. In the developed 3D model the geometry of the mine workings is incorporated in suited detail and resolution. Important findings from different model scenarios will be presented. The computational results are compared with field observations and geophysical measurements. Conclusions will be drawn with respect to the significance of the saltwater dynamics on the subsidence potential of the mine site.

Key Words Density dependent flow, deep salt mine, FEFLOW

Introduction

In the historical salt town of Staßfurt in the Federal State of Saxony-Anhalt, Germany, mining subsidence damages have caused severe economic losses in the past. As a result of the earthquake-like vibrations and the accompanying flooding of the salt mine Leopoldshall I/II and Heydt/von Manteuffel in the late 19th and the early 20th century approximately 800 buildings had to be dismantled (Jahnke et al, 2009). A research project called "dynamics of flooded salt mines and related cap rock stockworks" was launched to develop a sustainable land use concept for the urban and industrial areas within this historical mining site. Post-mining landscape development on top of the flooded mine openings of the salt mines along the salt saddle of Staßfurt is dominated by deformation and solution processes within the mining sites, especially within the area of the potash deposits, but also in rock salt or cap rock dominated structures. Mining subsidence damages could be observed as soil subsidence or a more severe collapse of the underground. This has already been analyzed within the BMBF-funded research project called "measures for sustainable hazard control for contaminated sites within mining related destabilization processes, exemplarily focusing on the conditions within the city of Staßfurt". This project however didn't make use of the possibilities of numerical flow and transport modeling to analyze the specific conditions within such areas. With the project presented within this paper the capabilities of such models should be analyzed in detail, especially focusing on:

- 2D scenario analyses using a density dependent transport model for selected cross sections
- 2D scenario analyses to describe the salt specific chemical precipitation processes related within oversaturated solutions
- 3D density dependent transport modeling
- 3D scenario analyses based on a hypothetic initial salt distribution regarding transport with and without anthropogenic influences

Because FEFLOW (Diersch, 2009) is one of the few commercial groundwater modeling systems which are able to describe fully integrated density dependent transport processes, this software was selected to be used for the above mentioned calculations.

Conceptual 2D simulations along representative longitudinal profiles

With the above mentioned conceptual 2D simulations it was basically intended to give insight in the dominating processes, boundaries and parameters to be considered for the 3D modeling. In cooperation with the BGR one existing geological profile was selected to be representative for these analyses (Fig. 1). For this profile the influence of dif-

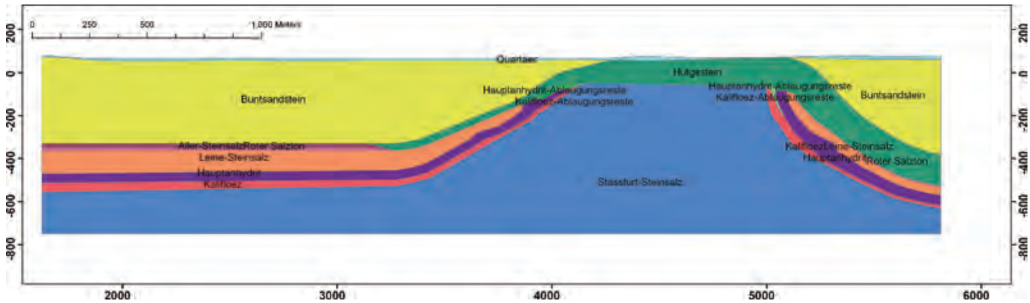

Figure 1 *Geological profile.*

ference boundary types as well as values have been analyzed in detail. Specifically the main river Bode, the existing extractions (drainage) as well as the outer boundary conditions have been studied. Furthermore, simulations have been carried out to test the influence of internal model settings, parameters as well as numerical solution schemes. All simulations were based on a quasi-stationary model setup, with the river Bode as the one and only internal hydraulic boundary condition. The resulting concentration distribution was defined as the initial concentration for the subsequently performed transient calculations, each simulating a period of 200 years. All simulations used the integrated density dependent flow and mass transport equations, based on the definition of the parameter density ratio α, which can be described by:

$$\alpha = \frac{(\rho_{max} - \rho_0)}{\rho_0} \quad (1)$$

To calculate the corresponding salt distribution additionally a definition of a lower and upper limit C_{min} and C_{max} is obligatory, by which the density ρ can be calculated for each concentration using;

$$\rho = \rho_0 \left[1 + \frac{\alpha}{(C_{max} - C_{min})} (C - C_{min}) \right] \quad (2)$$

Within all simulations a 1st kind Dirichlet boundary condition has been defined on top of the salt dome with a value of 345 g/L. A constant groundwater recharge rate of 90 mm/a was uniformly defined along the top of the complete model. Finally, the river Bode was represented by a 1st kind boundary condition with a constant water level of 52.6 m (asl = above see level).

The calculated scenarios showed that realistic results could only be obtained by a combination of extraction in the city area and a defined collateral inflow into the Buntsandstein. Assuming only an inflow on top of the existing main anhydrite, the simulations showed unrealistic salt concentrations in areas close to the surface.

Subsequently numerical 2D models have been set up to analyze processes related to two parallel salt species (NaCl, $MgCl_2$). To describe the interaction between the salt solutions within the mining facilities ($MgCl_2$-dominated Q-solutions) and the NaCl-dominated solutions of the overburden, as well as density dependent flow processes of multiple salt species and their chemical reactions (for example NaCl-precipitation) as a result of the interaction between the two above-mentioned solutions, a simplified ternary Na-Mg-Cl System has been used for the modeling. This approach has already been successfully applied to overcome the complex salt chemistry within mining facilities in other studies (Jahnke *et al.* 2010). With these 2D models it was intended to define a correct density, which describes the density driven processes in the Staßfurt area in a correct way. The models could however also be used to verify, whether an accurate description of the distribution of the two mentioned species could be attainable with the data available. Based on an empirical polynomial a relation between the solute $MgCl_2$ and the maximum possible NaCl concentration can be defined:

$$NaCl_{max} = -2.2\times10^{-9}\times MgCl_2^4 + 3.1\times10^{-6}\times MgCl_2^3 - 4.3\times10^{-5}\times MgCl_2^2 - 1.1\times MgCl_2 + 320 \quad (3)$$

Additionally a mixed density ρ_{mix} was introduced:

$$\rho_{mix} = 7.15\times10^{-4}\times MgCl_2 + 6.2\times10^{-4}\times NaCl + \rho_{H2O} \quad (4)$$

Different models and scenarios have been set up and calculated to analyze the dynamical reactions related to the solution and precipitation processes of the salt. Additional constitutive relationships have been defined and integrated to describe the precipitation driven cementation of the pores. These relationships were useful to limit the

***Figure 2** Exemplary result of a reduced porosity caused by chemical reactions and precipitation.*

maximum of precipitated salts. An interesting result of this approach is the fact that a relatively impermeable crust is evolved, which limits further mass transport processes to a large amount (Fig. 2).

Detailed 3D numerical flow and transport modeling

The model area for the 3D model covers an area of 88.5 km². The city of Staßfurt is located in the middle of the model area and the river Bode divides the area in two parts starting from the north-western towards the central eastern border. The area focusing on the salt mining sites with their potential dangers is therewith completely covered by the model. In a first step a horizontal triangular finite element mesh has been generated. The elements along the main river courses (Bode and Liethe), around the mining sites, around the extent of the salt saddle, along geological distortions like faults and fractures and around the extraction wells have a significant smaller size than the elements at the borders of the model. The generated mesh contains 57,174 elements and 28,682 nodes for each layer. The horizontal mesh is shown in Figure 3. In a second step the vertical discretisizing was based on the available data of a hydrogeological structural model. This setup was validated according representative longitudinal profiles. Besides the 12 hydrogeological layers which describe the main characteristics for the vertical mesh the hydrogeological structural model also includes two additional layers for units Keuper and shell limestone, which are located in limited areas in the northwestern part of the model. In total the model was therefore generated on the base of 14 hydrogeological layers. For numerical reasons however the final model was extended to 28 layers with totally 1,600,872 elements and 831,778 nodes. The applied permeability distribution and the description of the different geological units are listed in Table 1. An example of the different layers has already been shown in Figure 1. The geometry of the mining site could be repre-

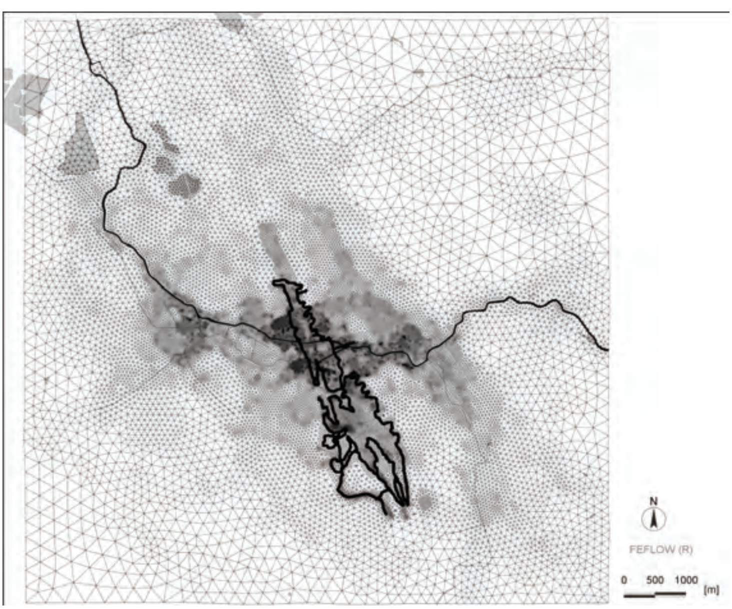

***Figure 3** Horizontal mesh of the applied 3D FEFLOW model.*

***Table 1** Applied layers within the 3D FEFLOW model.*

Layer	Unit	k_f (horiz.) (m/s)	k_f (vert.) ratio	Porosity (%)	Boundary (g/l)
1 - 3	Quaternary	$10^{-6} \sim 10^{-3}$	1	2,5 ~ 25	
4	Tertiary	$10^{-6} \sim 10^{-3}$	1	5 ~ 25	
5	Keuper	$10^{-6} \sim 2.5*10^{-5}$	1	5	
6	Shell limestone	$10^{-6} \sim 2.5*10^{-5}$	1	5	
7	upper Buntsandstein	$10^{-6} \sim 2*10^{-5}$	1	5	
8 - 10	middle Buntsandstein	$10^{-6} \sim 2*10^{-5}$	1	5	
11 - 18	lower Buntsandstein	$10^{-6} \sim 2*10^{-5}$	1/100 – 1/10	5	
19	Aller rock salt	$10^{-10} \sim 10^{-5}$	1/10	0,1 ~ 5	350
20	Red salt-bearing claystone	$10^{-6} \sim 5*10^{-6}$	1/10	1 ~ 5	
21 - 22	Leine rock salt	$10^{-10} \sim 10^{-5}$	1/10	0, 1 ~ 5	350
23 - 25	main anhydrite	$10^{-6} \sim 10^{-5}$	1/10	5	
26	Leine salt-bearing claystone	$10^{-8} \sim 5*10^{-7}$	1/10	1 ~ 5	350
27	rock salt between 2 potash layers	10^{-7}	1/10	5	350
28	Staßfurt rock salt	10^{-11}	1	0, 7	350 g/l

sented in the mesh by a horizontal mesh refinement. Because the pits basically follow the courses of the geological units (especially the potash horizon) a denser vertical setup of the model was not necessary. The rivers were idealized by 3rd kind boundary nodes. Also 4th kind boundary nodes were implemented. With these, the extraction pumps could be represented. Finally, 1st kind boundary nodes were used to estimate the collateral external inflow fluxes along the northeastern and southwestern boundaries.

The flow model was successfully verified by means of a representative one-day measurement at 92 groundwater observation wells within the top Quaternary and Tertiary layer. The influence of the salt transport on the hydraulic regime was neglected during this first stage.

In the next step, the calibrated model was transformed into a density-dependent transport model by defining mass transport related parameters and boundary conditions. The salt horizons were described by a constant value of C_{ref} for NaCl of 350 g/L. On the flanks an additional Cauchy boundaries have been defined. This is a mixed form between Dirichlet- (defined concentration) and Neumann (defined mass flux) boundaries. Starting from the Staßfurt potash horizon a global 1st kind boundary condition of 350 g/L was set. By specification of the salt release rate by means of a contact resistance with a transfer rate of $\Phi = 10^{-8}$ m/d the release of the salt could be constrained. Using these boundary types the released salt mass Q_{mass} (g/d) is defined as a function of the transfer rate Φ, the exchange area A, the salinity C and C_{ref}:":

$$Q_{mass} = A \cdot \Phi \cdot \left(C_{ref} - C\right) \quad (5)$$

A (m²) represents the area which is enclosed between 3 (horizontal) or 4 (vertical) of these boundary nodes. Along the southwestern as well as the northeastern boundaries a constant concentration of 100 mg/L (fresh water) was defined at those nodes which also have an external inflow boundary. Furthermore, a global density ratio of 0.245, a longitudinal dispersivity of 50 m and a transverse dispersivity of 10 m have been used in all computations.

Assuming that the drainage related extractions could be neglected a 500 year period was simulated (density dependent) until a quasi steady - state was reached. This state can be considered as a numerical equilibrium between the diffusive salt release out of the boundary salt layers and the salt outflow along the river boundaries (exfiltration). The resulting concentration distribution can then be regarded as geogenic and can be used as an initial concentration distribution for subsequent scenario simulations. By varying extraction rates of the drainage system pumps these scenario calculations were performed for a period of 100 years and could be used to gain a better insight in the relevant processes related to the subsurface saltwater distribution.

From the results of these simulations following conclusions could be drawn:

- The hydrogeological structure of the central area of the Staßfurt anticline must have played

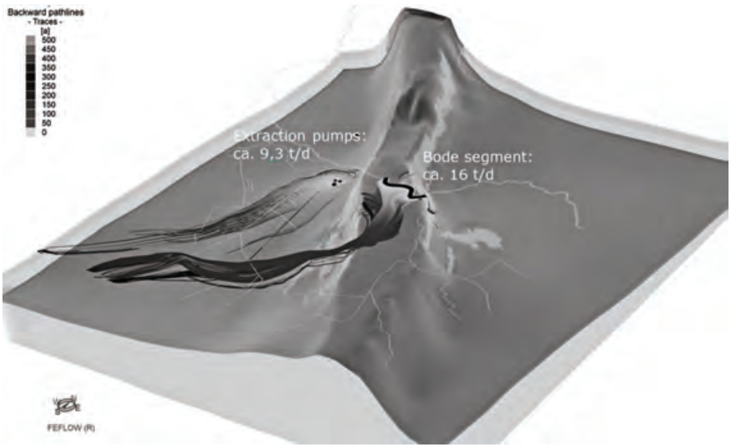

Figure 4 Exemplary analyses of the influence of extractions and rivers on mass fluxes using backward pathlines

a significant role in the development of the subsurface concentration distribution in Staßfurt.

- The river Bode functions as a drainage system. The interacting groundwater fluxes seem to be the driving force for the saltwater transport.
- Additionally, groundwater extractions change locally limited groundwater flow patterns und do therefore also influence the saltwater distribution.

Figure 5 finally shows calculated salt concentrations in the Quaternary aquifer (left) and the measured electrical conductivity by Helicopter Electro-Magnetics (right), which are the results from Subproject 2, BGR B2.1 (ref. also Siemon & Kerner 2010). The dark parts represent higher subsurface electrical conductivities, implying probably higher salinity of the groundwater. The figure shows a reasonably good agreement between the calculated salt concentrations and the measured electrical conductivity.

Conclusions

The numerical simulation and their results gave a better insight in the flow and mass transport processes in the study area. Especially the 3D mod-

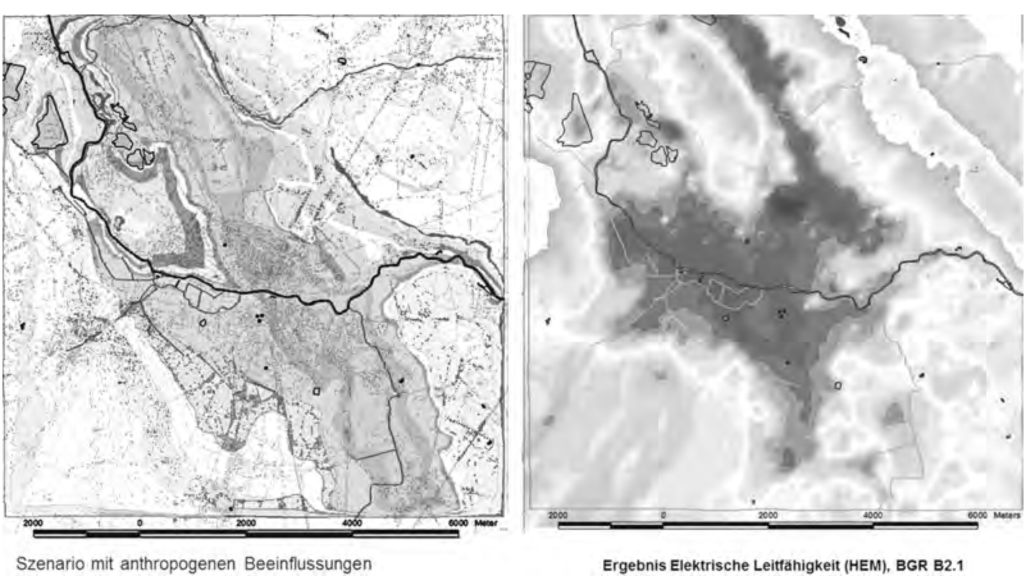

Figure 5 *Comparison of calculated salt concentrations in Quaternary aquifer with the results of measured electrical conductivity by Helicopter Electro-Magnetics (TV 2, BGR B2.1)*

eling also contributed to the fact that measured data could be critically analyzed in cases where a disagreement between observations and model results occurred. The developed techniques regarding data preparation and modeling can be used in other areas where mining consequential damages, subsidence problems, salt mining or related density driven hydrodynamics play a significant role. The mentioned 2D detail studies can be useful in such studies to gain a basic understanding of the local relevant processes in the study area.

Acknowledgements

This project was one of the subprojects of the joint research project “Dynamics of abandoned and flooded salt mines” financially supported by the Federal Ministry of Education and Research (BMBF) Germany, i.e. Subproject 6 with the Reference-No. 02C1516. The authors thank the project partners involved in the joint research project, especially Subproject 1 Brandenburg Technical University (BTU Cottbus), Subproject 2 Federal Institute for Geosciences and Natural Resources (BGR), Subproject 5 (IHU Stendal), Subproject 10 LIAG Leibniz. The authors also thank LAGB Sachsen-Anhalt for providing relevant data for the modeling.

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