Saltwater injection into a fractured aquifer: A density-coupled mass-transport model

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Abstract

The Werra-Kali potash mining region has a mining history for more than 90 years. The mining region is situated both in the Free State of Thuringia and the federal state of Hesse, Germany. Since 1925, high saline waters of potash productions have been injected into a confined, deep aquifer of the Permian Zechstein formation (carbonate rock aquifer).

The carbonate rock aquifer is a regional aquifer with extensive natural variations of salinity of geogenic origin, ranging from fresh to saline waters. Its overburden consist of the formation series “Obere Letten” of upper Permian, the Triassic Buntsandstein and Muschelkalk formations. The formation series “Obere Letten” consists of clay- or siltstone and hydraulically separates the carbonate rock aquifer and the Buntsandstein aquifers. The Buntsandstein is subdivided in the lower, middle and upper Buntsandstein, where the lower Buntsandstein is a regional aquifer and the middle Buntsandstein occurs partly as perched aquifer. The upper Buntsandstein is an aquitard and hydraulically separates the underlying middle Buntsandstein from the overburden Muschelkalk. Muschelkalk occurs in the southern part of the region, partly as perched aquifer. Finally, the quaternary sediments occur in river valleys and form local shallow aquifers.

Groundwater levels, salinity, and water levels in the nearby river have been monitored for several decades. The aim of the project was, based on available data and results of geological works and mining investigations, to develop a numerical groundwater model capable of simulating the impact of the injection regime of the past 90 years on regional flow patterns and solute transport underground and identifying possible relations between saltwater injections and the non-point (diffuse) saltwater inflows into the nearby river.

Key words: Mine water, salt water injection, density-dependent saltwater flow and transport, interaction of ground and surface water, numerical modeling, FEFLOW

Historical background

The Werra-Kali potash mining region has a mining history for more than 90 years (Rauche 2015). The mining region is situated both in the Free State of Thuringia and the federal state of Hesse, Germany (fig. 1). Since 1925, high saline production waters have been injected into a confined, deep aquifer of the Permian Zechstein formation (carbonate rock aquifer). Alternating duration, location, and timing, 62 wells were used to inject saline production waters. Injection reached its maximum in the middle of 1960‘s with up to 30 Mio. m³/a. At present, rates are less than 4 Mio. m³/a.

Surface elevations in the mining region vary from 180 m to 700 m above sea level. The carbonate rock aquifer occurs in a variable depth from -800 m below sea level to 440 m above sea level. The Werra rock salt with potash seams occurs below the carbonate rock (Plate Dolomite), separated by impermeable clay formations.

The carbonate rock aquifer is a regional aquifer with extensive natural variations of salinity of geogenic origin, ranging from fresh to saline waters with a total mineralization (TDS) up to 70 g/l (Skowronek, F. et al. 1999). It is overlain by the formation series “Obere Letten” of upper Permian, the Triassic Buntsandstein and Muschelkalk formations. The formation series “Obere Letten” consists of clay- or siltstone and hydraulically separates the carbonate rock aquifer and the Buntsandstein aquifers. The Buntsandstein is subdivided in the lower, middle and upper Buntsandstein, where the lower Buntsandstein is a regional aquifer and the middle Buntsandstein occurs partly as perched aquifer. The upper Buntsandstein is an aquitard and hydraulically separates the underlying middle Buntsandstein from the overburden Muschelkalk. Muschelkalk occurs in the southern part of the region, partly as perched aquifer. Finally, the quaternary unconsolidated sediments occur in river valleys and form local shallow aquifers. Fig 2 schematically shows the hydrogeological situation in the Werra potash mining region.

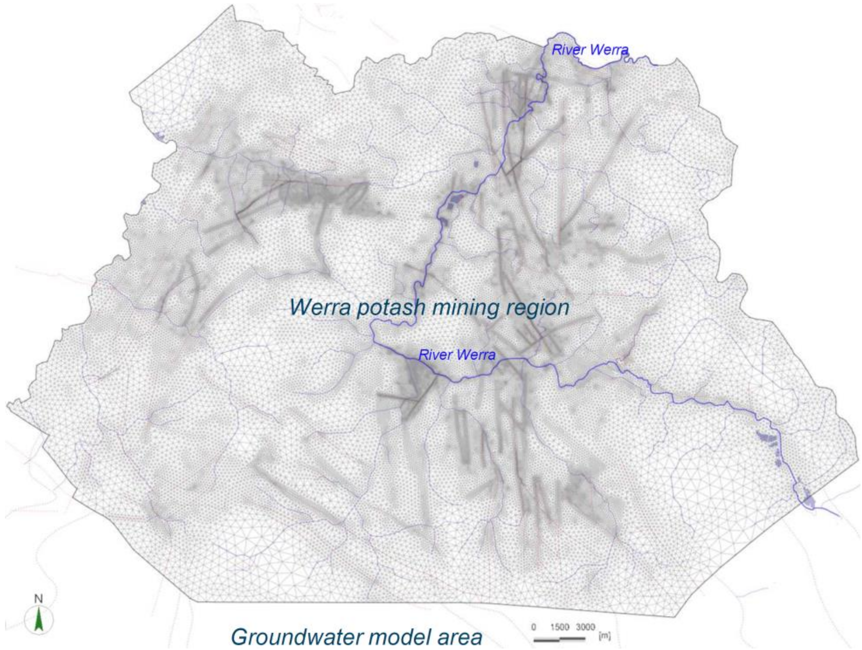

***Figure 1** Location of the Werra potash mining region and groundwater model area.*

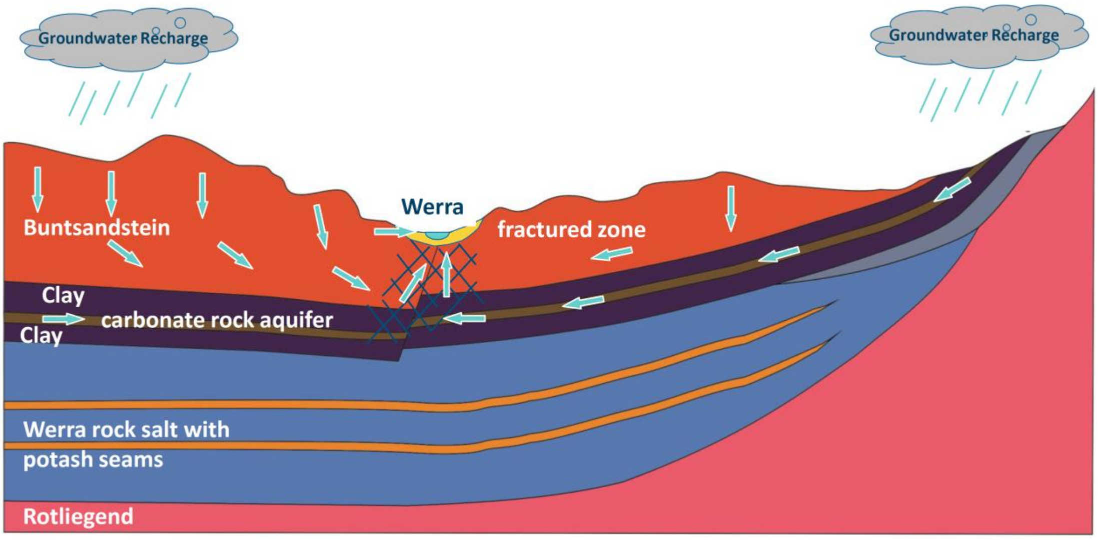

***Figure 2** Schematic hydrogeological situation in Werra potash mining region.*

Groundwater levels, salinity, and water levels in the nearby river have been monitored for several decades. Earlier investigations estimated the fraction of injected saline water, which passes the overburden to form non-point (diffuse) inflows to the main river to amount to app. 30%.

The aim of the project was, based on available data and results of geological works and mining investigations, to develop a numerical groundwater model capable of simulating the impact of the injection regime of the past 90 years on regional flow patterns and solute transport underground and identifying possible relations between saltwater injections and the non-point (diffuse) saltwater inflows into the nearby river.

Model concept and methods

Both a two and a three-dimensional density-coupled flow and mass-transport FEFLOW® model (Diersch 2014) were built based on a hydrogeological model of the region.

The 2D density-coupled flow and mass-transport model with an area of about 1000 km² was firstly established in the year of 2008, consisting only of the confined carbonate rock aquifer. The model was first calibrated for steady state flow conditions and subsequently for transient conditions between 1925 and 2007. The simulation results of the 2D model helped to understand the general system behavior from a modelling point of view and to describe the movement and dispersion of the injected saltwater in the deep carbonate rock aquifer. Yet, a possible up-coning towards the overburden in well-defined small leakage zones could not be analyzed in this 2D space. In the following years, additional boreholes have been explored and hydrogeological studies have been carried out, building a strong basis for the development of a 3D density-coupled mass-transport model.

The development of this 3D density-coupled flow and mass-transport model started in 2011. This model covers a study area of around 1220 km² and considers the complicated multi-layer aquifer system of the carbonate rock aquifer, overlain by siliciclastic Buntsandstein sediments, Muschelkalk and quaternary sediments. The total thickness of the represented hydrogeological formations is up to 1300 meters. The 3D numerical model developed with the code FEFLOW consists of 28 numerical layers with approx. 4 Mio. Finite elements. The density ratio of the density-coupled saltwater flow and transport is up to 1.21 [-].

Objectives of the 3D model developed were:

- Description of the dynamic groundwater levels and concentration developments of TDS in the carbonate rock aquifer and possibly in the overburden formations as a result of the injection activities over the whole period from 1925 to 2010 (transient calibration),
- Description of the movement and dispersion of the injected saltwater (represented by means of TDS) within the aquifer, as well as groundwater movement in the whole model domain,
- Verification of the preliminary 2D-model results,
- Scenario calculations with respect to various injection regimes.

The (from a modelling point of view) highly dynamical injection rates, inevitable density effects in the modelling domain, a large study area and the long simulation period were the main challenges of the project. The model calibration followed the concept shown in Fig 3. The transient calibration of the density-coupled saltwater flow and transport model of app. 90 years was carried out iteratively.

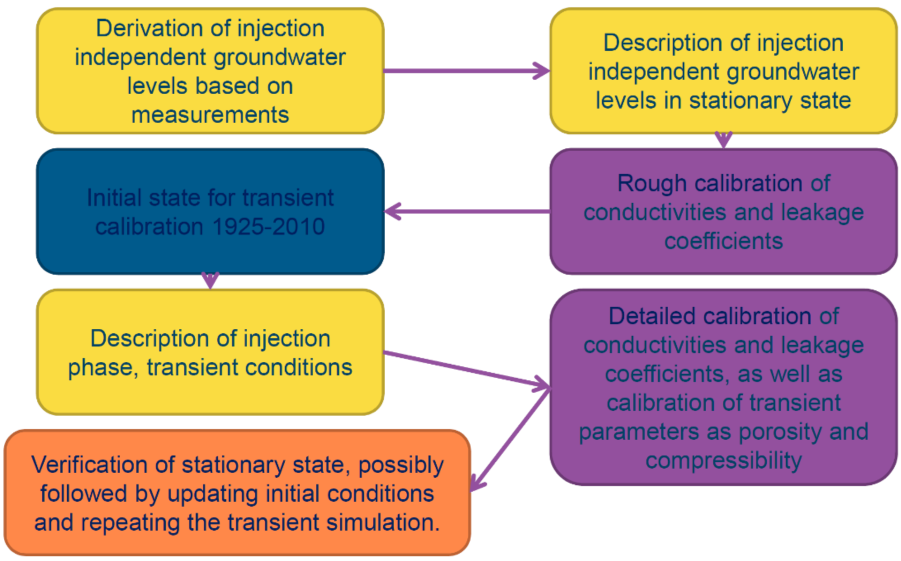

Figure 3 *Concept of the model calibration.*

Main results of the calibration

Evaluation of calibration results was based on:

- Comparison of simulated groundwater levels (hydraulic heads) with measurements in available monitoring wells (75 in the carbonate rock and 138 in the overburden formations),
- Comparison of simulated TDS with measurements in available monitoring wells (52 in the carbonate rock and 134 in the overburden formations),
- Comparison of simulated diffuse inflow (non-point sources) into the river

Fig. 4 exemplarily compares simulated hydraulic heads and TDS with corresponding measurements for a carbonate rock well. The well is situated at the south-western part of the model region and has a distance of app. 10 km to the injection site.

Simulated diffusive inflows to the river in comparison to calculated diffusive inputs based on measured chloride concentrations are shown in Fig. 5.

Fig. 6 shows the subsurface spatial distribution of simulated TDS (end of 2010) (left) in comparison to airborne electromagnetic data (right), where red color indicates comparable high TDS concentrations (left) versus high conductivity (right). Figures 5 and 6 confirm the good agreement of diffuse inflows both in sum over time, as well as at a high spatial resolution.

In general, the calibration results show a good match between simulated and observed heads as well as TDS concentrations in the carbonate rock and overburden formations. A good agreement of simulated diffusive inflows into the river in comparison to calculated diffusive inflows was achieved. The 3D density-coupled flow and mass-transport model reproduces plausible regional distributions of hydraulic heads and TDS in the carbonate rock and overburden formations in Werra potash mining region. The model helps to understand and confirm the general system behavior and to investigate the movement and dispersion of the injected saltwater in the complicated multi-layer aquifer system (Fig. 7).

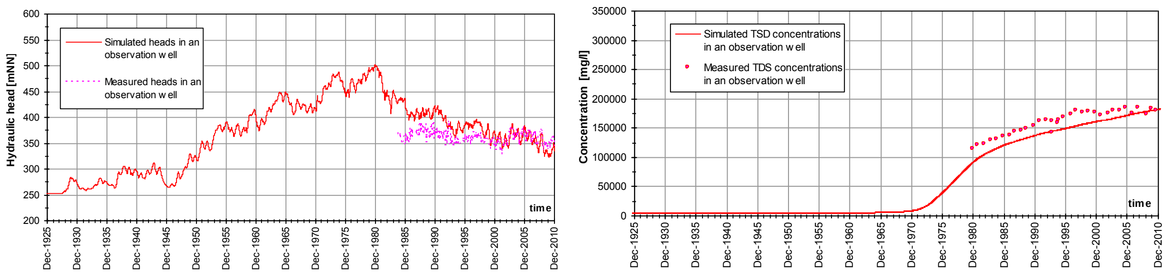

Figure 4 *Comparison of simulated heads and TDS with corresponding measurements in an observation well.*

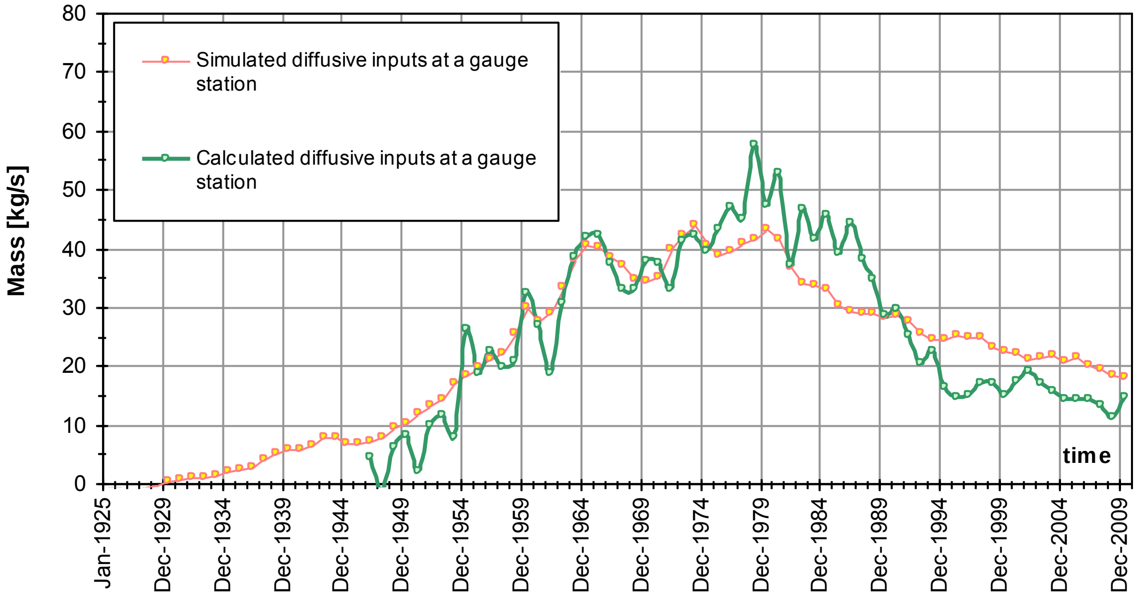

Figure 5 *Comparison of simulated diffusive inflows into the river with the diffusive inflows calculated based on measured chloride concentrations at a gauge station.*

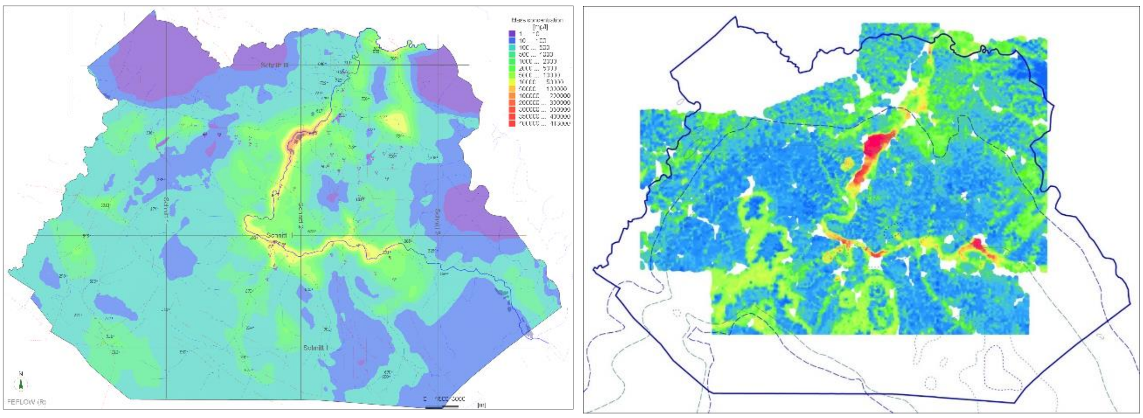

Figure 6 *Comparison of the distribution of simulated TDS near to surface (left) with results of measured airborne electrical resistivity (right), where red color indicates comparable high TDS concentrations or high conductivity, respectively.*

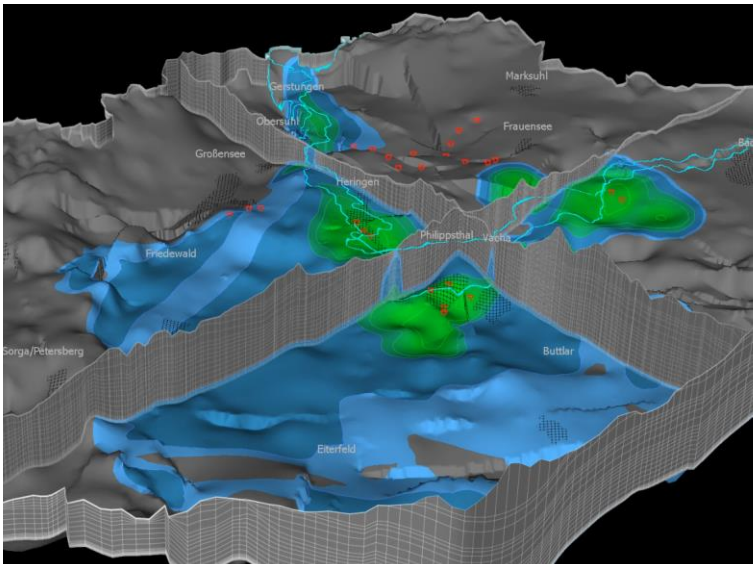

***Figure 7** 3D-View of the three dimensional density-dependent salt water transport in the confined carbonate rock aquifer.*

Summary

Although simulations with the 2D model were very useful in tracking the dispersion of injected saltwater in the carbonate rock aquifer, the necessity of the 3D approach was clearly confirmed during the second phase of the project. With the 3D model, further analyses with respect to groundwater recharge in the upper aquifers, which are partly used for drinking water supply, could be conducted. Besides a good match between observed and calculated heads as well as concentrations, the results of the 3D model additionally confirm the observed impact on diffusive inflows. By means of scenario and/or sensitivity studies, the impact of various injection strategies on the whole groundwater system was further analyzed. Accordingly, the following can be stated:

- Potash mining is related to strong environmental constraints;
- In order to meet these environmental demands, a Control Management System should be used;
- For the Werra potash region, part of this Control Management System consists of a 3D density dependent groundwater model based on the FEFLOW modelling framework;
- The model describes heads, concentrations and diffusive inflows into the Werra river on a regional scale and was crucial to confirm and improve the understanding of the long-term processes related to brine injection;
- The model can further be used for scenario simulations of various injection strategies;
- The model is flexible enough to account for future/new measurements and to include further site investigations;
- Nevertheless, only a combined monitoring and modelling approach can represent the whole groundwater system adequately.

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