Geothermal energy from a flooded mine: a hydraulic model

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Abstract The mines in the Rhenish Massif have left large-scale, complexly branched underground structures behind. These highly permeable areas crosscut the otherwise only slightly permeable layers of the Rhenish Massif. With the closure of the mines in the 1960s the mine workings were flooded. Groundwater ascending through the shafts is generally drained through the deep tunnels. Thermal heat pump techniques can be used for heating with this overflowing water. Additionally the large amounts of stored mine water can also be used for geothermal heating. A numerical hydraulic model is needed in order to ascertain at which locality it is possible to extract a defined volume of mine water at a defined temperature without causing a decrease in the potential of the discharge.

Key Words flooded mines, modeling, flow and heat transport

Introduction

Mining in the Rhenish Massif has left large-scale, complexly branched underground structures. These highly permeable areas (e.g. shafts, galleries, workings) are in parts more than 1,000 meters deep and crosscut the otherwise only slightly permeable, weakly metamorphosed predominantly clay to silt-sand layers of the Rhenish Massif. The project site is located in the northern Rhenish Massif, the so called Siegerland-Wied ore district. Mined ores were mainly Siderite ($FeCO_3$) and galenite (PbS) but also sphalerite (ZnS) and copper sulfides. The geological layers are characterized as fractured aquifers with a weak permeability and a very low porosity. Due to mining, these layers are now drained by a system of highly permeable shafts, galleries and backfilled areas. These different structural units dominate the hydraulic system of the mine. With the closure of the mines in the 1960s their drainage also ceased and the mine workings were flooded. This led to the situation that groundwater ascending through the shafts is generally drained through the deep tunnels (topographically the deepest tunnel with contact to the surface) of the mine (Wieber & Ofner 2008). Depending on the given locality, deliveries from these deep tunnels of up to 35 L/s at temperatures of up to 25 °C are known. Thermal heat pump techniques can be used for heating with this overflowing water.

In addition to the geothermal use of the overflowing water, the large amounts of stored mine water can also be used. A hydraulic model is needed in order to clarify at which locality it is possible to extract a defined volume of mine water at a defined temperature without causing a decrease in the potential of the discharge.

The main tunnels and shafts dominate the hydraulic conditions of a flooded mine and are integrated in the model as 1D-discrete feature elements. Their flow regime is calculated by the law of Hagen-Poiseuille. The 1D-structures (e.g. galleries, shafts, rolls) represent over-dimensional heat pumps with respect to heat transport. Backfilled workings commonly show very good permeabilities and high storage capacities, they are modeled as areas with higher permeability compared to the surrounding rock. The rock matrix itself can be regarded as a three-dimensional element. Anticline structures and fault zones can also give rise to good hydraulic conductivities. If such structures of important dimension are located in the project area they will be considered in the (three-dimensional) model.

Methods

In a first step, a two-dimensional thermohydraulic (Finite Element) model with FEFLOW was set up. For this model several simplifications are necessary. The geological rocks (Lower Devonian, Siegen-Stufe, Obere Siegener Schichten (Thünker 2008)) are characterized by a mean coefficient of permeability of $1 \cdot 10^{-7}$ m/s and a porosity of 0.1. Hence the aquifer is characterized as an aquitard with a very low hydraulic conductivity and a low productivity. These parameters are from literature data on the geology of the area. As the whole model region is situated in a not nearer subdivided geological layer, these parameters are used for the whole surrounding matrix.

Different model schemes became emerged because the two-dimensional model should deliver varying information about the hydraulic effectiveness of the different mining structural units. Thus, in the two-dimensional model only a small part of the whole flooded mine is examined. This part

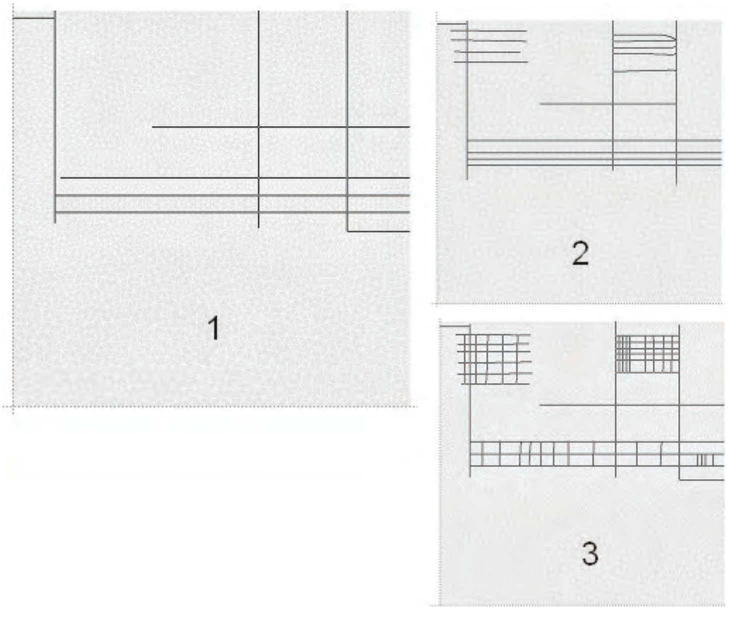

Figure 1 *Geometry of the mine, position of the discrete feature elements in the three model schemes.*

consists of three deep shafts in the northern part of the mine. In the first scheme (figure 1, 1) these shafts are only connected by deep galleries linking the shafts with each other. In the second scheme (figure 1, 2) also the shallow galleries without links to other shafts are added. In the third scheme (figure 1, 3) the so called ore rolls, which connect the galleries with themselves (independently, if they are in the lower or deeper parts of the mine) are embedded in the model geometry. All shafts, galleries, and ore rolls are characterized as one-dimensional discrete feature elements (figure 1) in FEFLOW and laminar flow is calculated by the law of Hagen-Poiseuille

This means that the mining structures are embedded within the low permeable rock matrix as water filled pipes with a laminar flow regime. The parameters characterizing the 1D-discrete feature elements (inter alia after VDI 4640) are listed in table 1.

In a next step, several scenarios with pumping wells and infiltration wells in the two-dimensional model shall deliver first results on changes in flow and heat regime through artificial geothermal use (besides the planned use at the deep adit).

Results

The amount of water (and its temperature) leaving the mine via the deep tunnel is automatically measured every 15 minutes since July 2009 (figure 2). These values are used to check and calibrate the thermohydraulic model.

Figure 2 shows that the water temperature is almost stable around 17 °C and that it is only little affected by the air temperature. No matter whether it is winter or summer time, water leaving the mine maintains a nearly fixed temperature; only small changes between 0.1 and 0.2 °C are measured. The amount of water is influenced by the amount of precipitation. At the state of research so far, there is a time lag of about 30 days before a large peak of precipitation can be detected in the discharge (excepting the snow melting in January 2011).

In addition the chemistry of the water at different sites (e.g. different shafts, partially different depth, the outflow of water at the deep tunnel) is examined (see also IMWA 2011 contribution of Wieber & Streb). In figure 3 the Schoeller-diagram shows the present chemical composition of the mine water from the shaft of mine A, from the discharge at the deep tunnel of mine A and also from one shaft of mine B. The water can be character-

Table 1 *parameters of the discrete feature elements.*

structural unit	cross-section area [m^2]	corrected hydraulic aperture [m]	conductivity of fluid [W/mK]	capacity of fluid [$10^6 J/m^3/K$]
shafts	16	2	0.59	4.15
galleries	4	1	0.59	4.15
ore rolls	1	1	0.59	4.15

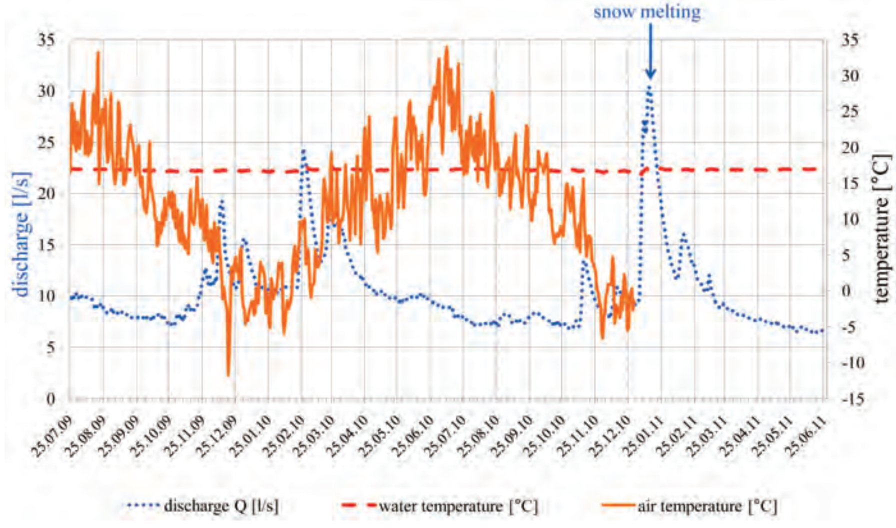

Figure 2 *daily average of the mine water discharge and mine water temperature at the deep tunnel of the mine. Air temperature from the weather station Siegen of the German Meteorological Service.*

ized by Furtak & Langguth (1968) as predominantly earth alkaline bicarbonate water. The chemical composition of the stowed water in the shafts (also in different depths) in different parts of the mine and at the deep adit is nearly identical. Compared to the chemical analysis from Heyl (1954) (during the active period of mining) different mixing effects have occurred since the flooding of the mine so that a homogeneous chemical composition is available today.

As far as they are still accessible today, depth profiles of the shafts (temperature and electrical conductivity of the water) were measured. In figure 4 the depth profile of two different shafts of the mine (A and B) and at two different times (mine A, March 2009 and July 2010) are shown. The depth profiles show that the temperature and electrical conductivity does not change much over the depth. There are also no bigger changes from the snapshots in time.

During the active period of mining temperatures reached up to 30 °C in the deeper parts of the mine (Fenchel 1985 & Heyl 1954). From the depth profile measurements a homogeny temperature over the depth is found today. These mixing effects, as they also can be seen in the chemical analysis, are caused by gaslift and convection and results in a system of communicating pipes (Wolkersdorfer 2006).

For the two-dimensional model several important facts on the general hydraulic conditions were discovered. Combined from all model results the deep, interconnected galleries represent the main hydraulic pathways. For the realisation of

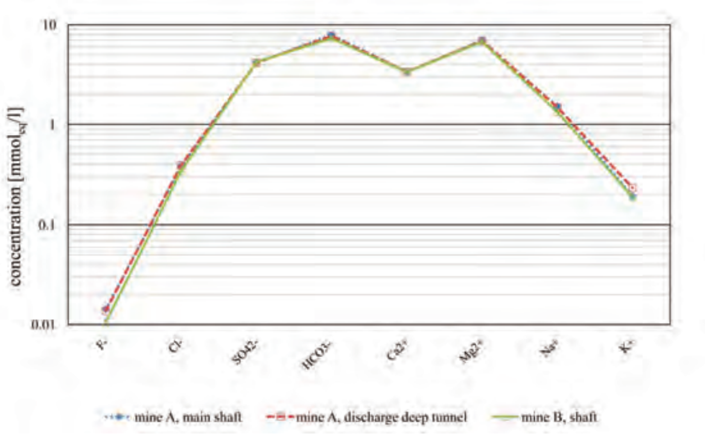

Figure 3 *Schoeller-diagram of homogeneous mine water chemistry.*

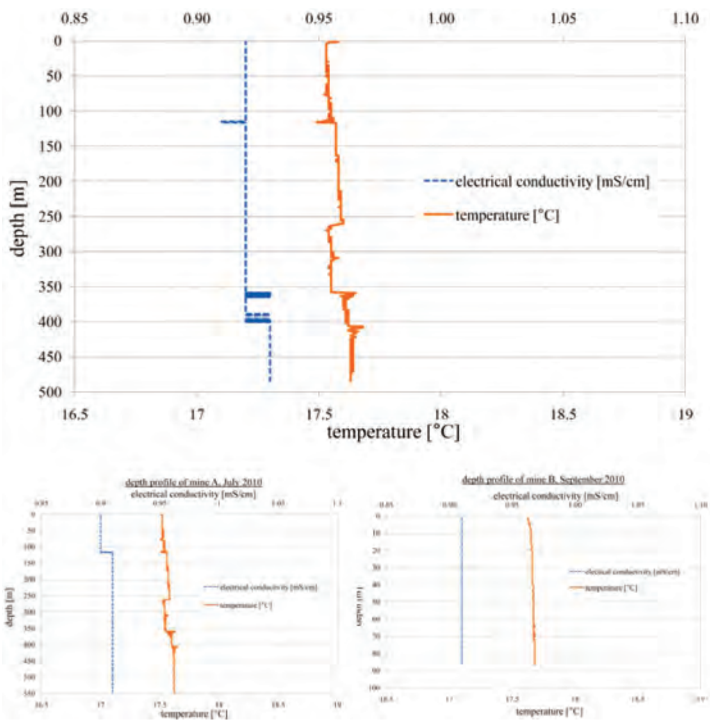

Figure 4 *depth profiles (electrical conductivity and temperature) of the measured shafts.*

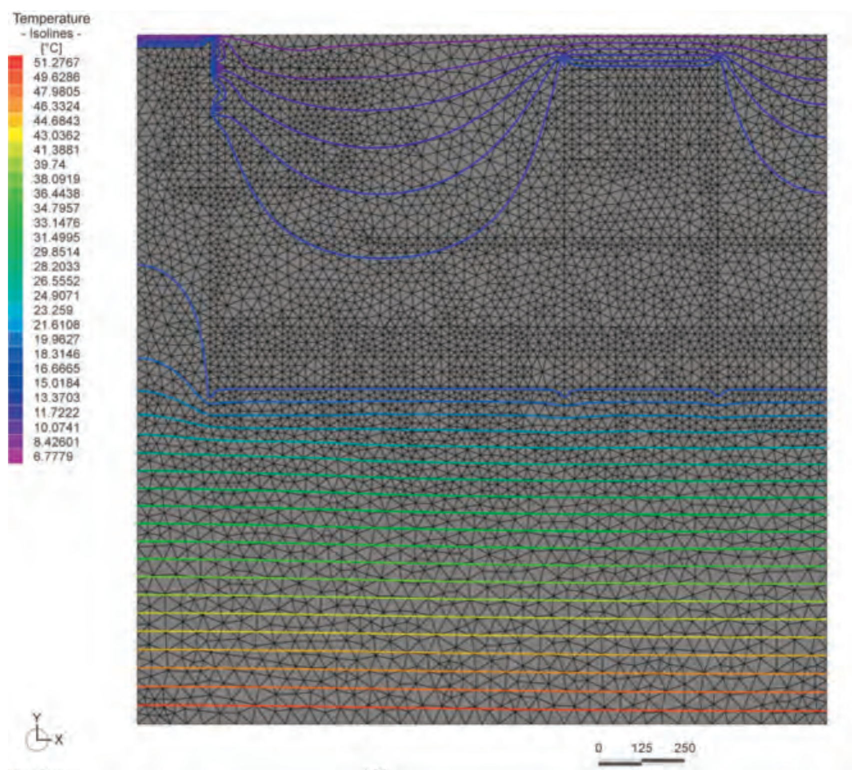

Figure 5 *Modeled temperature conditions for scheme 3 under stationary conditions.*

the overall hydraulic conditions of the mine also the lower galleries without connection to the neighboured shafts seem to be needed. On the other hand the ore rolls which connect the galleries among themselves do not have such a big influence on the main hydraulic conditions, so that for the three-dimensional model this large amount of structural units is not needed. The model calibration is achieved by the discharge of water and its temperature at the deep tunnel.

Figure 5 shows the modeled temperature distribution in model scheme 3 with deep galleries, shallow galleries and ore rolls.

Conclusions

With the two-dimensional model it is shown that the flow and temperature field of the flooded mine can be modeled and that a useful reduction of the structural units is possible. Taking the results from the two-dimensional model into account the three-dimensional model will be developed.

Outlook

In the two-dimensional model gaslift (and the associated turbulent conditions) are not yet considered, this needs to be taken into account too. As Wieber & Streb (2011) implied, the measured velocity of flow in the shafts in the project area is between 0.8 mm/s and 3.6 mm/s, a Reynolds number of > $Reb_{krit}b$ = 2,300 is expected. Taking this into account would mean that flow in shafts (and contingently also in the galleries) needs to be modeled under turbulent conditions. The complete necessary geometry of the mine will be built up as a three-dimensional FE-model. The different layers will represent the galleries are responsible on the hydraulic conditions of the model.

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