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The Reutilization of a Small Coal Mine as a Mine Thermal Energy Storage

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ABSTRACT

The aim of the **German HEATSTORE sub-project** is to create a technically and fully functional high temperature mine thermal energy storage (HT-MTES) pilot plant for the energetic reuse of an abandoned small coal mine, with the emphasis on an extended operating and monitoring phase during the project lifetime of three years. The generated data can be exploited for the implementation and dissemination of future deep geothermal storage systems. The conceptual idea is based on the storage of seasonal unutilized surplus heat during the summer from solar thermal collectors within the mine layout and the usage of stored thermal energy during the winter for heating purposes of the institute buildings of the International Geothermal Centre (GZB).

1. INTRODUCTION

The concept of this pilot plant aims at the reutilization of an abandoned small coal mine, which is directly located under the premises of the International Geothermal Centre (GZB) in Bochum (Figure 1), as a high temperature mine thermal energy storage. This area also includes the drilling and test facility site of the GZB, on which the Bochum Research and Exploration Drilling Rig (Bo.REX) is currently located. This leads the way of a very cost effective exploration of the flooded small coal mine in a depth of approximately 75 m below ground. Currently, the groundwater level resides at a depth of approximately 21 m below ground. This is constantly measured in the monitoring wells R1 and O1-4 (depicted as blue circles in Figure 1). Overall, the small coal mine produced 37.043 tons of coal during its life cycle. Based on a calculation with a coal density of 1,35 g/cm³, we can assume a void volume of approx. 27.439 m³. This volume does not include any drifts and shafts.

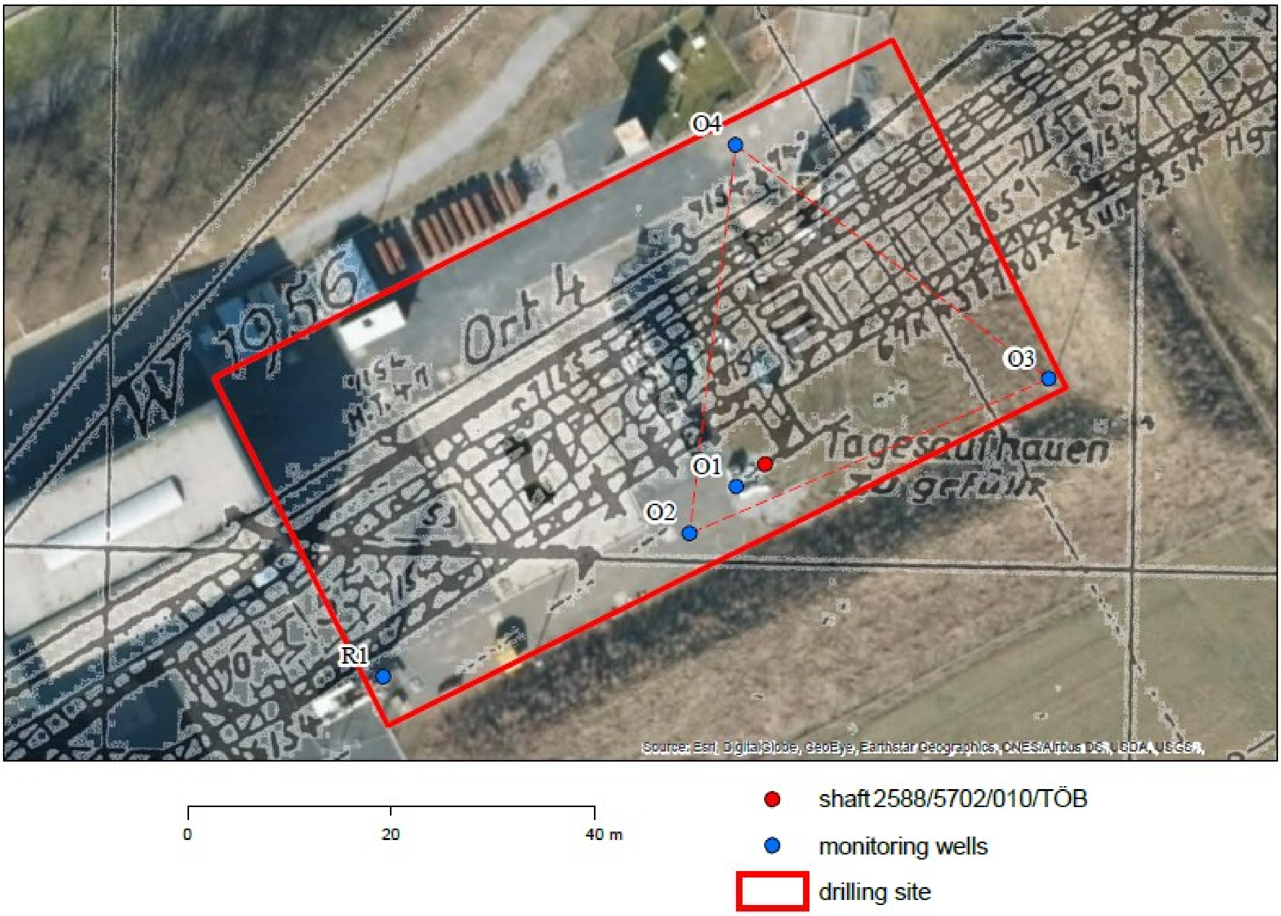

Figure 1: Location of a small coal mine below the GZB premises

Considering the effect of mine subsidence, the remaining void volume will most likely be in the range of approx. 10 %. Utilizing a Δt of 50 K within the mine water, a heat capacity of approx. 165 MWh, which resembles the yearly heat demand of the GZB compound, could be stored within dedicated drifts and former mining areas of the small coal mine for the winter heating season. Based on this first evaluation, the yearly GZB heat demand could be substituted by emission free solar thermal energy. After the pilot phase is concluded the integration of the small coal mine thermal energy storage into the district heating network of the “unique Wärme GmbH” could be tackled, as two CHP plants (9 MW_{th}) were put in operation in September/2018 (Stadtwerke Bochum GmbH 2018) in a very close proximity of approx. 350 m to the foreseen high temperature mine thermal energy storage pilot plant.

2. HISTORICAL BACKGROUND

During the years of the coal shortage after the Second World War, many small coal mining operations were established throughout the Ruhr area. This period lasted for approximately fifteen years, until the beginning of the coal crisis in 1957, which made these small coal mines highly unprofitable.

The small coal mine was part of this development and was owned by a company from Southwestern Germany. Daily production rates were between 40 to 50 tons, which didn’t fulfil the expectations of the owner, as these production rates didn’t recover the substantial investment costs. Table 1 gives an overview of the life cycle of the small coal mine, during its operational phase from 1953 till 1958 (Viëtor 2012).

Table 1: Production summary

Year	Production in t	Comment	Employees
1953		Commissioning	
1954	10.528	Max. production	49
1955	10.250		57
1956	8.346		54
1957	7.919		48
1958		Closure	

3. MINE WATER STATE OF TECHNOLOGY

The idea of obtaining thermal energy from an inoperative coal mine has already been pursued for a long time, although to a comparatively limited extent in the present time. Up to this point a pilot plant has not been established, in which the possibility of thermal energy storage in a former coal mine has been considered. Well-known executed projects concerning the utilization of mine water include:

• The Mijnwater-project (Verhoeven et al. 2013) in Heerlen (Netherlands), whereby an already completely flooded and no longer accessible mine layout was accessed through directional drilling technology.

• The building of the School of Design at the Zeche Zollverein (Bleicher 2007) in Essen (Germany), which is heated by 28°C warm mine water, originating from the mine drainage of the RAG AG.

• The utilization of mine water of the former Robert Müser (Willmes 2014) coal mine in Bochum (Germany) as an energy source for the heat supply of two schools and the mine drainage station in Bochum. Within this pilot plant the 20°C warm mine water, which originates from the mine drainage of the RAG AG from a depth of 570 m below ground, is being used.

• Seven operational mine water utilization plants (LANUV 2018) in Saxony (Germany), which can be categorized as shallow geothermal reservoirs. A deep mine water project is currently being implemented at the West Saxon University of Zwickau, where mine water from a depth of 625 m below ground with a temperature of 26°C is planned to be extracted.

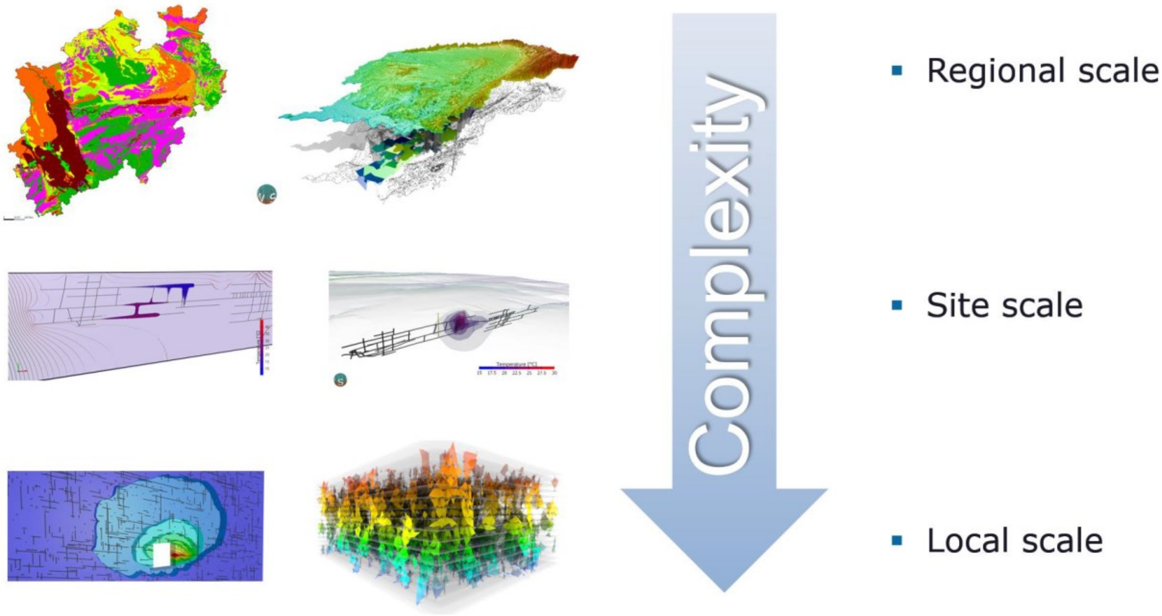

Figure 2: Stepwise modelling approach

4. MODELLING APPROACH

In this project numerical groundwater flow and heat transport modelling is used to estimate the influence of a mine thermal energy storage pilot plant on the groundwater aquifer, the prediction of the physical environment and the assessment of the impacts of different pumping rates. Later on, monitoring programs will be developed and competing demands on the groundwater resource can be evaluated.

Understanding heat transport during the planning of geothermal plants is complicated by heterogeneities in the subsurface and cyclical plant loads. Based on the extensive mining situation in the Ruhr area within a complex geologic setting a stepwise modelling concept was developed (Figure 2).

The conceptual model was developed using maps and cross sections, existing data and data gathered during the field investigation of this study. It forms the basis for the understanding of the groundwater occurrence and flow mechanisms of the site, and is used as basis for the numerical groundwater modelling.

The concept comprises the following three scales with an increasing level of detail:

• Regional scale (>10.000 km²)

The Regional scale includes geology and the transient mining (dewatering) influence in the regional area. Large scale transient groundwater models have been built to analyse the regional flow system. They deliver boundary conditions for the site scale.

• Site scale (~10 km²)

The Site scale models the detailed underground mining works at the small coal mine site within a local geological setting. It enables planning, dimensioning and optimization of the thermal energy storage pilot plant in terms of heating and cooling cycles.

• Local scale (<1 km²)

At the local scale different parts of the pilot plant are modelled with a high detail. It is used to estimate local effects like the influence of fractures or different (residual) mine void volumes.

4.1 Regional scale

The regional scale consists of the two existing models “Groundwater Model Northrhine-Westfalia” (Figure 3) and groundwater model “Münster Cretaceous Basin” (Figure 4).

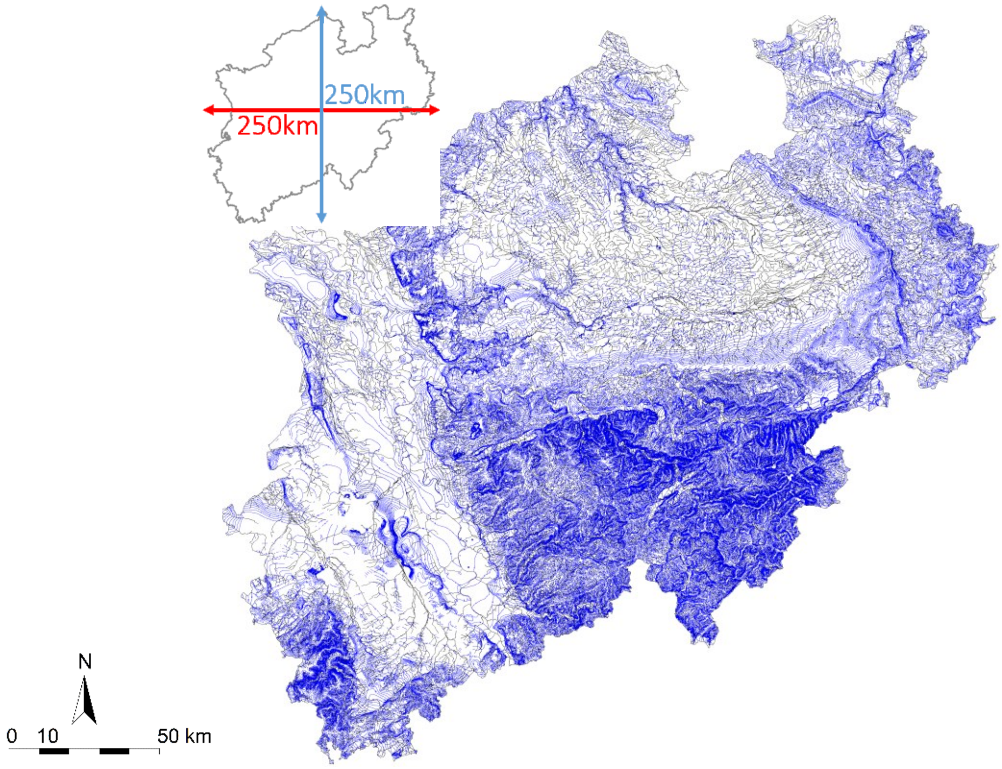

Figure 3: Groundwater Model Northrhine-Westfalia

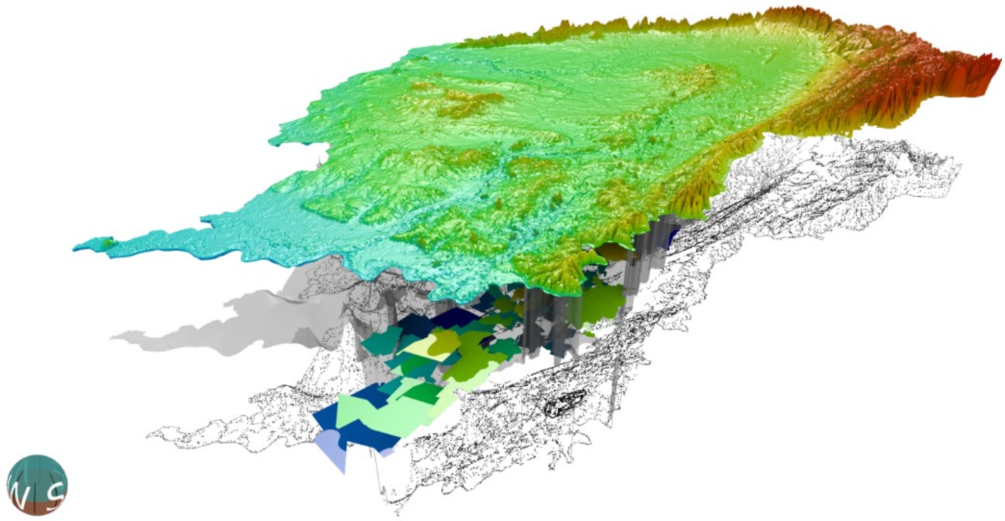

Figure 4: Groundwater model "Münster Cretaceous Basin"

With an area of about 14.000 km^2 the 3D groundwater model covers the whole Cretaceous Basin in the area "Münsterland" and delivers information about the regional geology as well as the influence of the complex mining setting (Figure 4). Modelling the impacts of mine dewatering and flooding on a regional scale as for the basin presents many challenges including the appropriate discretization of mine voids and the accurate modelling of layered aquifer systems. To predict the environmental impacts of both the historic mining activities and future operations, a detailed conceptual model of the aquifer systems and a 3-dimensional model of the mining areas were incorporated into a numerical groundwater model. This model was used to simulate the dewatering and post-closure rebound of the water tables in the vicinity of the mine.

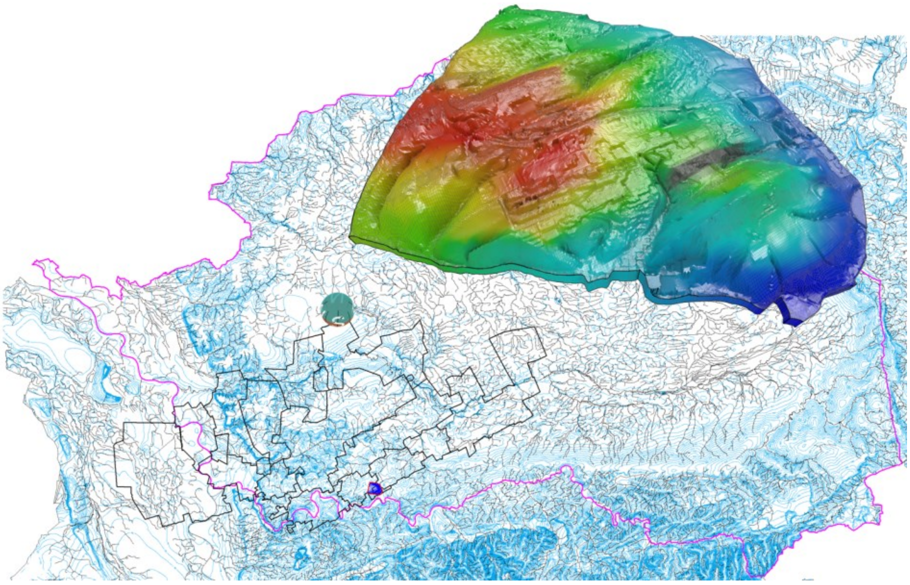

Figure 5: Location of the site scale model (inset at the top) in correlation to the regional model (blue area in the background map)

4.2 Site Scale

The 3D site scale model covers an area of ~10 km² with a vertical resolution of 18 layers. It models the local aquifer system and includes the digitalized mine void model (Figure 5). It includes a detailed geologic layer distribution with the local syncline structure and coal seams at the site. In accordance with the developed conceptual model, the upper model layer simulates the upper aquifer system and the lower layers represent the deeper underlying aquifers and aquicludes. In contrast to the regional scale, underground mine workings were integrated into the model domain as 1D fracture elements aligned to the depth of the mine voids.

4.3 Local scale

Carboniferous rock at the site is highly fractured. Groundwater flow takes place in the fracture network where advection and gravity forces are the dominant processes. For characterizing the flow and transport phenomena in the fractured rock on a local scale, it is necessary to model a discrete fracture matrix system (König 1998).

The local fractured Carboniferous rock is exposed in a sandstone pit close to the site. Measurements of the local carboniferous fracture data have been performed by Witthüser and Himmelsbach (1997) including a tracer test between two boreholes. The results were analyzed to get the statistic parameters for a stochastic fracture generation which was performed in a local model domain:

Table 2: Statistical parameters of the measured clusters

cluster	orientation in space	spherical angle Q	spherical variance ϕ	concentration parameter k
I	(a,f) = (274°,88°)	8.2°	0.95	16
II	(a,f) = (71°,6°)	8.2°	0.95	17
III	(a,f) = (309°,4°)	12.3°	2.35	16

The clusters of preferred orientations are determined by identifying their respective maximum densities and choosing an appropriate selection angle for each cluster. A symmetrical Fisher (i.e. spatial normal) distribution is assumed for each cluster. In the local model fractures are generated by using the analyzed statistical data and are approximated by plane elements. The volume elements of the surrounding porous rock matrix are generated by means of a layer technique. With a fixed potential head assigned at the inflow and outflow boundary a combined hydraulic conductivity (porous media/fractures) can be calculated and transferred to the site model (Figure 6).

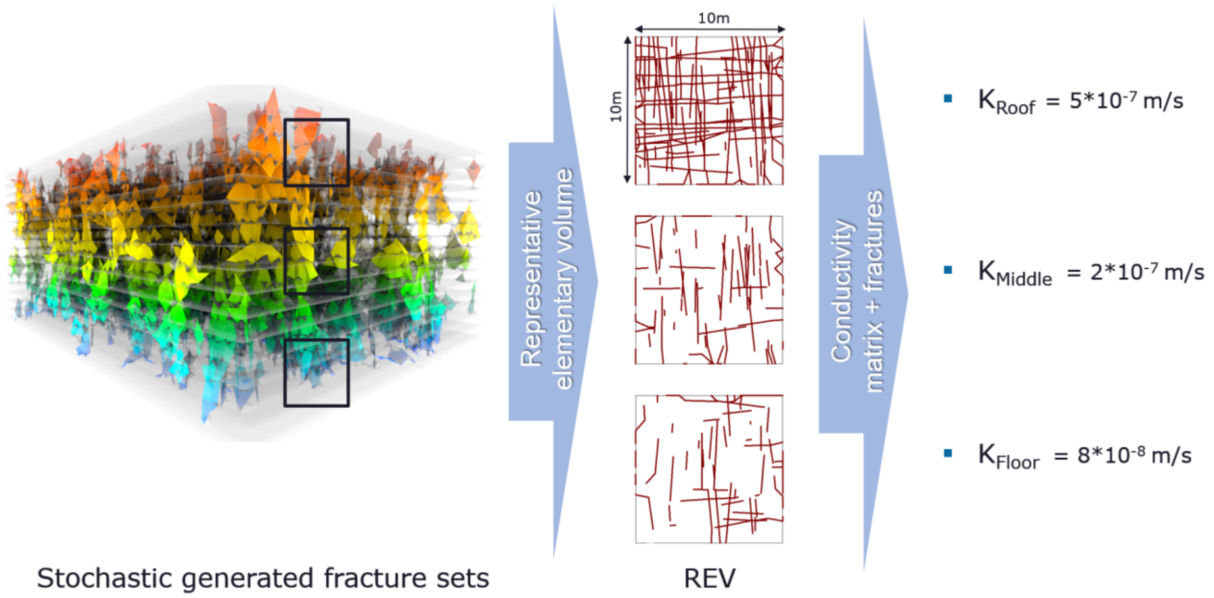

Figure 6: By stochastic fracture generation estimated hydraulic conductivities (Carboniferous)

5. COMPUTATIONAL APPROACH AND SOFTWARE

The software code chosen for the numerical modelling work was the 3D groundwater flow and transport model SPRING, developed by the delta h Ingenieurgesellschaft mbH, Germany (König 2018). The program was first published in 1970, and since then has undergone a number of revisions. SPRING is widely accepted by environmental scientists and associated professionals. SPRING uses the finite-element approximation to solve the groundwater flow and transport equations. This means that the model area or domain is represented by a number of nodes and elements. Hydraulic and thermic properties are assigned to these nodes and elements and an equation is developed for each node, based on the surrounding nodes. A series of iterations are then run to solve the resulting matrix problem utilizing a pre-conditioning conjugate gradient (PCG) matrix solver for the current model. The model is said to have "converged" when errors reduce to within an acceptable range. SPRING is able to simulate steady and non-steady flow, contaminant transport, density dependent transport as well as heat transport, in aquifers of irregular dimensions and different model layers with varying thicknesses as well as out-pinching model layers are possible.

6. SCENARIOS AND PRELIMINARY RESULTS

Heat transport in groundwater is driven by advection, hydromechanical dispersion and the heat conduction in fluid and matrix. It can be mathematically described by the generalized heat transport equation:

$$\underbrace{\frac{\partial(n\rho S_r c_w T)}{\partial t}}_{\substack{\text{storativity term}\\ \text{in the fluid}}} + \underbrace{\frac{\partial\big((1-n)\rho_s c_s T\big)}{\partial t}}_{\substack{\text{storativity term}\\ \text{in the matrix}}} + \nabla\big(\underbrace{n\rho S_r c_w(\vec{J_k} + \vec{J_d} + \overrightarrow{J_{m,w}}}_{\substack{\text{energy flux}\\ \text{in the fluid}}} + \underbrace{(1-n)\rho_s c_s \overrightarrow{J_{m,s}}}_{\substack{\text{energy flux}\\ \text{in the matrix}}}\big) = \underbrace{q(T_{in} - T)}_{\substack{\text{source}\\ \text{terms}}}$$

Material parameters:

n porosity [-]

ρ, ρ_s density fluid, density matrix [kg/m³]

S_r saturation [-]

c_w, c_s specific heat capacity of fluid and matrix [(Ws)/(kgK)]]

Variables:

v distance velocity [m/s]

T temperature [K]

T^{in} temperature in- and outflow [K]

t time variable [s]

q = div v [1/s]

Energy flux:

$\overrightarrow{J_K} = \vec{v}\,T$ advection

$\overrightarrow{J_m} = -\mathrm{D}\nabla T$ hydro mechanical dispersion, D is the symmetrical dispersion tensor [m^2/s]]

$\overrightarrow{J_{m,w}} = -\lambda_w \nabla T$ heat conduction in fluid, λ_w is the heat conductivity of the fluid [W/(mK)]

$\overrightarrow{J_{m,s}} = -\lambda_\vartheta \nabla T$ heat conduction in matrix, λ_s is the heat conductivity of the matrix [W/(mK)]

The first terms on the left hand side are the storativity term in the fluid and the matrix followed by the energy flux in the fluid and the matrix. The right hand side is the source term. For steady-state modelling the storativity term vanishes.

6.1 Scenario A

Figure 7 shows the setup for a steady state heat transport calculation (scenario A). Warm water with a temperature of 35 °C and a flow rate of 1.600 m^3/a is infiltrated at level 4 (MP1) while cool water is extracted with the same flow rate at level 1 (MI1).

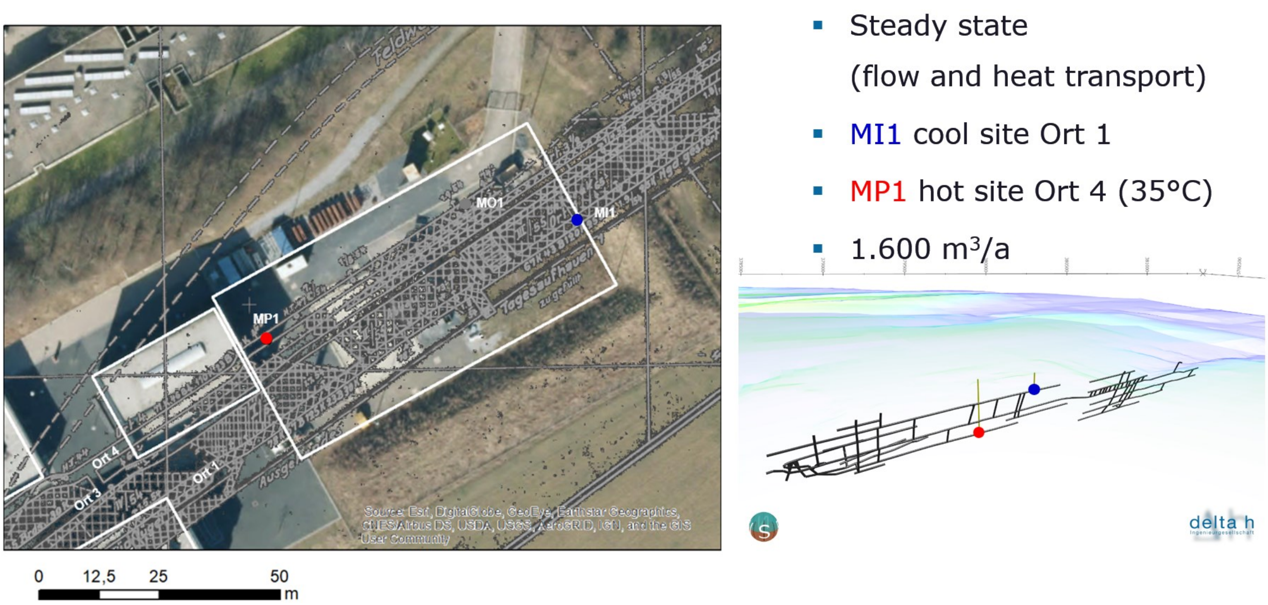

Figure 7: Site setup for heat transport calculations (scenario A)

Figure 8 shows the calculated temperature distribution of the steady state flow and heat transport calculation (scenario A). A temperature plume is developing from the infiltration point to the West in direction of the (open) mine void. Because of the steady state calculation type the result can be classified as “worst case” as the plume is much bigger than it would be under transient conditions.

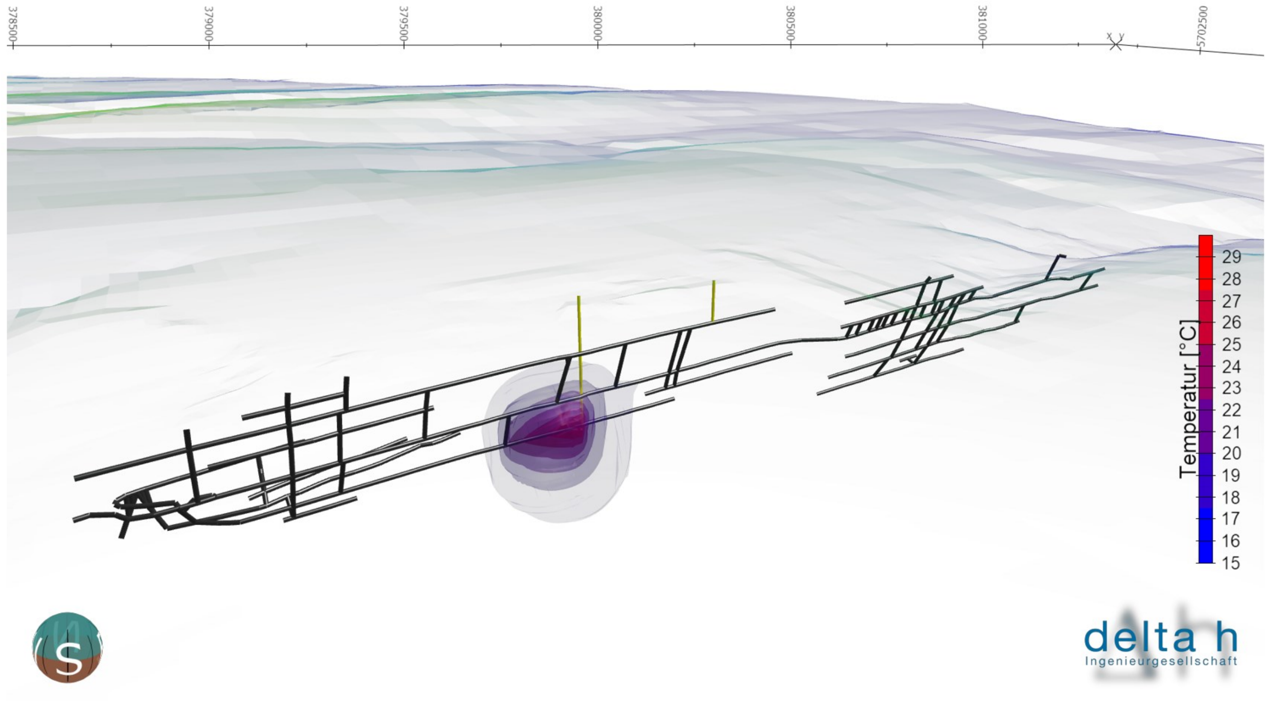

Figure 8: Steady state temperature distribution (scenario A)

6.2 Scenario B

To estimate the impact of different pumping locations and for optimization the model can be used to calculate different scenarios. Figure 9 shows the setup for an alternative scenario B. Warm water with at temperature of 35 °C and a flow rate of 1.600 m^3/a is infiltrated at level 1 (MI1) while cool water is extracted with the same flow rate at level 4 (MP1).

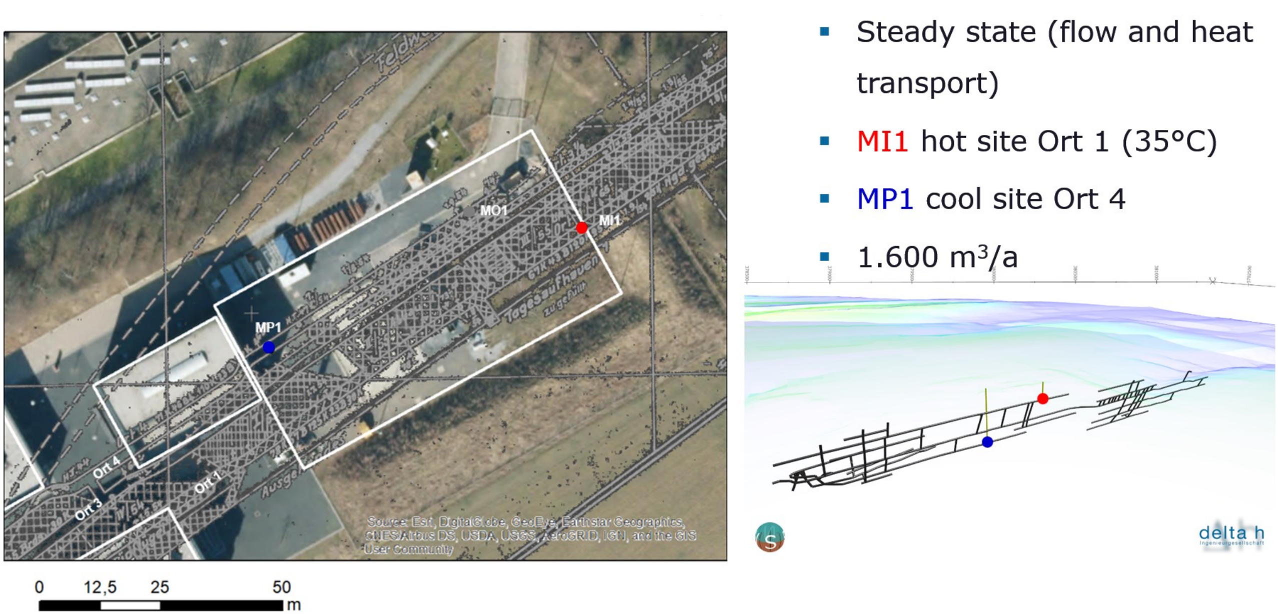

Figure 9: Site setup for heat transport calculations (scenario B)

Figure 10 shows the calculated temperature distribution of the steady state flow and heat transport calculation (scenario B). A temperature plume is developing from the infiltration point following the mine void down and to the East. Because of the steady state calculation type the result can be classified as “worst case” as the plume is much bigger than it would be under transient conditions.

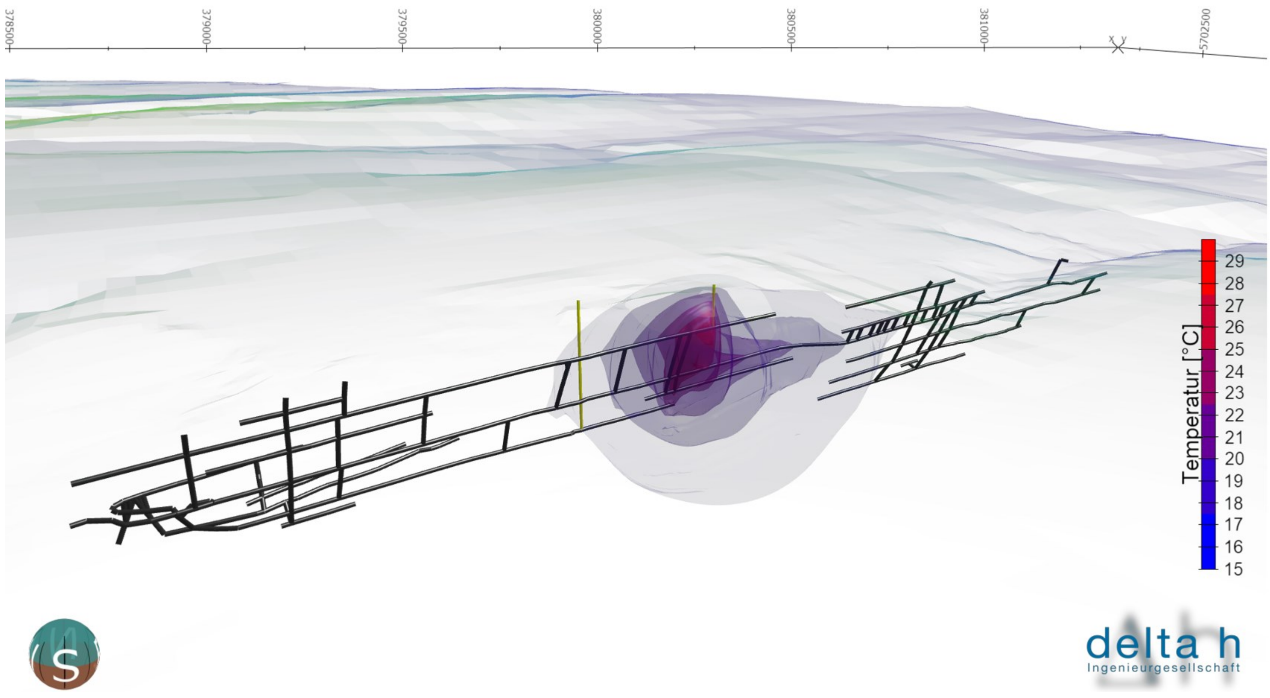

Figure 10: Steady state temperature distribution (scenario B)

ANALYSIS AND DISCUSSION

Geothermal storage systems are a promising technology for the heating and cooling of buildings with renewable energy sources. The energy performances of these systems depend on the properties of the mine layout, the surrounding rock mass and the groundwater flow. In this work, the operation of a seasonal mine thermal energy storage pilot plant has been simulated, using a finite-element subsurface flow and heat transport modelling code (SPRING).

The relative influence of the regional and local mining system, hydrogeological and thermal rock property has been investigated, running a set of simulations and analyzing the resulting fluid temperatures. At this time, comparing the intermediate results, we observe that the condition of the mine is a very important property for the hydraulic pathways, which needs to be further investigated in order to optimize the overall performance of the system. It should be noted that thermal conductivities of Carboniferous rocks show a slight decrease (Mücke 1962), while being exposed to temperatures of up 90°C. Therefore heat conductivity of the surrounding rock heavily influences the resulting fluid temperatures, and in-situ tests should be carried out, in order to predict the plant operation accurately.

CONCLUSION & OUTLOOK

The development of diversified storage capacities will have a great impact on the future promotion of renewable energy sources. Within the Ruhr area, unutilized mining infrastructures in combination with available surplus heat from (solar) power plants and industrial processes, resemble a vast potential for large heat storage capacities. Out of this reason, fundamental research in the field of high temperature seasonal heat storage in abandoned mines has to be conducted for further technology development and establishment of large scale storage systems.

During the upcoming project phase, the implementation of three exploration wells into the existing mine layout of the small coal mine is foreseen. Pump and tracer tests will determine possible storage capacities. In the case of a successful technical implementation of the small mine thermal energy storage, the design and operation results would be scalable to other locations in Germany and worldwide.

REFERENCES

Bleicher, V. (2007): Zukunft Erde, Energie heute und morgen - Ein Ausblick, zuletzt geprüft am 01.04.2019.

König, C., Becker, M., Diehl, A., Seidel, T., Rosen, B., Rüber, O. & Zimmermann, C. (2018): SPRING - Simulation of Processes in Groundwater. - 5. Aufl.: 478 S.; Witten,

König, T., Rüber, O. & König, C. (2017): Erstellung der Grundwasseroberfläche für das gesamte Bundesland NRW als Datengrundlage für das Kooperationsprojekt GROWA+ NRW 2021 (unveröffentlicht). - Im Kooperationsprojekt GROWA+ NRW 2021, Im Auftrag vom Landesamt für Natur, Umwelt- und Verbraucherschutz Nordrhein-Westfalen; Witten (delta h Ingenieurgesellschaft mbH).

LANUV (2018): LANUV-Fachbericht 90, zuletzt geprüft am 21.03.2019.

Mücke, G. (1962): Untersuchungen über die Wärmeleitfähigkeit von Karbongesteinen und ihre Beeinflussung durch Feuchtigkeit im Zusammenhang mit der Wärmeübertragung des Steinkohlengebirges an die Grubenwetter. Aachen, T. H., F. f. Bergbau u. Hüttenw., Diss. v. 26. Juni 1962, Aachen.

Willmes, J. (2014): Nutzung von Grubenwasser zur Wärmeerzeugung - Projektbeispiel. In: bbr-Sonderheft Geothermie.

Witthüser, K.; Himmelsbach, T. (1997): Evaluation of fracture parameters for stochastic generation of fracture networks. In: Gottlieg, J. et.al. (Eds.): Field Screening Europe, pp. 183–186, Kluver Academic Publishers, Dordrecht

Stadtwerke Bochum GmbH (2018): Wärmeversorgung für Querenburg und Ruhr-Universität gesichert. Online verfügbar unter https://www.stadtwerke-bochum.de/industrie/Service/pressecenter/pressemeldungen_rss_feeds.html, zuletzt geprüft am 28.10.2019.

Verhoeven, R.; Willems, E.; Harcouët-Menou, V.; Boever, E. de; Hiddes, L.; Op't Veld, P.; Demollin, E. (2013): The EC REMINING-lowex project in Heerlen the Netherlands: transformation from a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure Mine Water 2.0. European Geothermal Congress 2013. Pisa (Italien). Online verfügbar unter http://www.chri.nl/upload/art%20REMINING%20Lowex%20Mine%20water%200613.pdf, zuletzt geprüft am 01.02.2018.

Viëtor, W. (2012): Kleinzechen in Bochum-Querenburg - eine Zeiterscheinung nach dem Zweiten Weltkrieg, Witten-Heven.

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