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Complex Scientific Analysis in Geothermal Exploration in the Pannonian Basin

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ABSTRACT

The deep sedimentary Pannonian Basin has unique geology and hydrogeology. Below its unconfined gravitational flow system, there are some aquifers with outstanding geothermal potential. This paper will give the details of a complex investigation into one of the most promising geothermal reservoirs in Hungary. In addition to revealing its geological and hydrogeological features, the paper discusses the detailed technical investigations and calculations that were carried out to determine the viability of geothermal energy utilization from the investigated aquifer. Although there is a considerable risk given the high salt content of the groundwater and the extreme over-pressure, the results obtained are very promising and convincing for further investments in the near future.

Between two wells in a fractured limestone geothermal reservoir, the flow was investigated using two different methods in order to characterize tracer transport phenomena. The knowledge of reliable tracer transport simulation is key to the determination of the petrophysical properties of geothermal reservoirs. In the first simulation, the flow was considered in an equivalent plane fracture using the Hele-Show flow approach. The second method replaced the fractured system with an equivalent porous layer in which a Darcy flow develops. The Hele-Show flow is described by analytic complex variable functions, while the Darcy flow is determined applying the finite difference simulation method. The obtained results exhibit adequate correlation. The agreement is especially strong between the injection and production wells.

1. INTRODUCTION

A pre-feasibility study was elaborated to prepare the implementation of the first Hungarian geothermal pilot power plant. The hydraulic and thermodynamic performance of the fractured geothermal reservoir was modeled for this purpose. The flow pattern in the fracture and the heat transfer in the adjacent rock were determined using the method of hydrodynamical singularities and the transient heat conduction equation. The same phenomenon was modeled from another aspect: the simulation of tracer transport in the fractured reservoir. The hydraulic and tracer transport modelling is based on a finite difference method applying MODFLOW 2000 and MT3DMS simulation software. If the results obtained by two independent approaches are similar, the adequacy of each method is confirmed.

2. DESCRIPTION OF THE SOFTWARE USED FOR MODEL CONSTRUCTION

The hydraulic and contaminant modelling using the MODFLOW-2000 and MT3DMS simulation software are used for evaluation of the available options of tracer transport in a fractured geothermal reservoir. An equivalent porous media (EPM) was assumed with the Darcy-flow approach during numerical modelling. This modelling study facilitates a hydraulic and transport modelling approach for the efficient investigation and management of fractured geothermal reservoirs. Flow and transport modelling and simulations based on the all available information can help the decision makers to find the most effective and environmentally friendly solution for the injection strategy. Here, the Processing MODFLOW for Windows 7.0 (PMWIN Pro) software (Chiang and Kinzelbach 2001) was used for different simulations. The finite-difference MODFLOW 2000 module (Harbaugh et al. 2000) is an industrial standard used to create accurate and reliable 3-D groundwater flow models. Besides the groundwater quantity issues, the PMWIN Pro can handle tracer or contamination transport processes using its well-known MT3DMS program. In most cases, transient-state simulations are required to follow up the consequences of the time dependent processes. The PMWIN PRO modelling environment provides experts with convenient input options, where boundary conditions, hydrogeological parameters, and all other necessary information can be given.

MODFLOW is a U.S. Geological Survey modular finite-difference flow model. This computer code can solve the groundwater flow equation. The governing partial differential equation solved numerically in MODFLOW is given in the following form:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, $K_{yy,}$ and K_{zz} are the values of the hydraulic conductivity along the x, y, and z coordinate axes (L/T), h is the hydraulic head (L), W is the volumetric flux per unit volume representing the sources and sinks of groundwater, for which negative values denote extractions and positive values denote injections (T^{-1}), S_S is the specific storage of the investigated aquifer (L^{-1}), and t is time (T). This program is widely used throughout the world by hydrogeologists to simulate the flow of groundwater through aquifers. The code is free software, written in the FORTRAN language, and can be compiled and run on the DOS, Windows, or UNIX operating systems. Since its original development in the early 1980s, the USGS have released four major versions of this code, and it is now considered to be the *de facto* standard industrial code among the groundwater specialists for aquifer simulation. Currently, there are many actively developed commercial and non-commercial graphical user interfaces for MODFLOW.

The MODFLOW-2000 version was released on July 20, 2000. Many new packages and enhancements were also released, including new solvers and stream and saturated flow packages. The following packages of MODFLOW-2000 were used to describe the different source and sink terms during the above-mentioned simulation activity of the present studies: General-Head Boundary, Drain, Evapotranspiration, Reservoir, Lake, and Well and Recharge.

There are several graphical interfaces in MODFLOW, which often include the compiled MODFLOW code. These programs provide convenient means of supplying the input data for creating MODFLOW models. Commercial MODFLOW programs are typically used by governments and consultants for the practical application of MODFLOW to real-world groundwater problems. The applied PMWIN-Pro may be considered as a professional commercial version of MODFLOW.

A three-dimensional flow model considering three-layers was implemented with the help of the MODFLOW-2000 module in the present study. This model was used to characterize the main hydrostratigraphic units of the investigated area, namely the lower Pleistocene ”waterworks” aquifer, the middle Pleistocene aquifer, and the unconfined upper aquifer that also contains a shallow groundwater aquifer. The input data required for the flow model was readily available from earlier geological and hydrogeological prospecting activity.

In addition to the flow model, a transport model was also built to investigate the several groundwater quality issues. The transport movement investigations were carried out in the field-study with the help of the MT3DMS model (Zheng and Wang 1999), where MT3D stands for the Modular 3-dimensional transport model, and MS denotes the multi-species structure for accommodating add-on reaction packages. MT3DMS has a comprehensive set of options and capabilities for simulating the advection, dispersion, diffusion, and chemical reactions of contaminants in groundwater flow systems under the general hydrogeologic conditions. The MT3DMS was developed for use with any finite-difference flow model, such as MODFLOW, and is based on the assumption that changes in the concentration field will not affect the flow field appreciably.

The partial differential equation describing the fate and transport of contaminants of the species k in a three-dimensional space in transient groundwater flow systems can be written as follows:

$$\frac{\partial(\phi C^k)}{\partial t} = \frac{\partial}{\partial x_i}\left(\phi D_{ij}\frac{\partial C^k}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(\phi v_i C^k) + q_s\, C_s^k + \sum R_n \quad (2)$$

where A denotes porosity of the aquifer (dimensionless fraction), C^k is the dissolved concentration of species k (M/L^3), t is time (T), $x_{i,j}$ is distance along the respective Cartesian coordinate axis (L), $D_{i,j}$ is the hydrodynamic dispersion coefficient tensor (L^2/T), v_i is the seepage or linear pore water velocity based on the Darcy equation (L/T), q_s is the volumetric flow rate per unit volume of aquifer representing fluid sources and sinks (1/T), C_s^k is the concentration of the source or sink flux for species k (M/L^3), and $\sum R_n$ is the chemical reaction term ($M/L^3/T$).

Based on the available geological and tracer material information, a three-dimensional steady-state flow model was created. Of course, the time variable (up to 400 days) was involved in the transport modelling phase to describe the tracer concentration changes in the simulated formation. In the model, the thickness was 10 m, the length was 2000 m and the width was 1200 m. A finite difference grid was applied for simulations. The basic grid size is 25 m. A pair of wells (a doublet) was placed into the model symmetrically. A finer grid mash was applied around the wells to increase the numerical accuracy of the simulation calculations. The basic properties of this 10 m – thick limestone aquifer were given. The bottom elevation of the model is -2900 m, and the top elevation is -2890 m. Hydrostatic pressure (300 bar or 30 MPa) distribution was assumed. This means that the initial hydraulic head of the model was 100 m. The natural hydraulic gradient (I) was zero. No-flow boundary conditions were applied. The natural replenishment rate is zero. Concerning the water balance, the change of the stored water resource is zero, as the assumed production and injection wells have the same productions rates (Q = 50 l/s). This also means that only horizontal flow occurred in the investigated aquifer. Estimation was applied to derive the hydraulic conductivity and porosity values. The permeability was 1000 mDarcy, corresponding to a hydraulic conductivity of 0.864 m/day. The porosity was 0.05. Based on these data, the hydrodynamic or flow model was built. Figures 1-3 describe the most important information associated with the flow model.

Then, the MT3DMS module of the PMWIN Pro package was applied to simulate the transport processes of the investigated fluorescent tracer as a function of time and space. Besides advection, the phenomena of hydrodynamic dispersion were also taken into account. The adsorption and decay of the tracer were neglected in the investigated limestone environment. The length of the simulation was 400 days. Tracer concentration maps were drawn at different times. The tracer and dispersion properties were estimated from the special literature.

It was assumed that the tracer (1200 l) is pumped into the formation in the injection well for 15 minutes at the beginning of the simulations. When the tracer injection was finished, the tracer concentration was about 5 g/l or 5000 mg/l, or 5,000,000 $\mu g / l$ in a 50 m^3 fracture space.

Then, the tracer transport was simulated in space and time. Figures 4-6 show the main results of the transport modelling concerning concentration distributions and breakthrough curves.

3. SUMMARY

The flow between and around the two wells was investigated using two different methods. The streamlines were determined using an analytical method of hydrodynamic singularities. The path lines following the tracer motion were calculated by a numerical procedure based on finite differences. The same phenomenon was approached from two different aspects.

Streamlines and path lines are congruent in a steady flow. Thus, in spite of some different details of the applied mathematical tools, considerable similarities can be recognized, especially between the wells. Far from the wells and close to the arbitrarily taken boundaries of the reservoir, streamlines and path lines may have different patterns. Naturally, there are some differences between the two models used in the approximations, but the high degree of similarity indicates the adequacy of both models.

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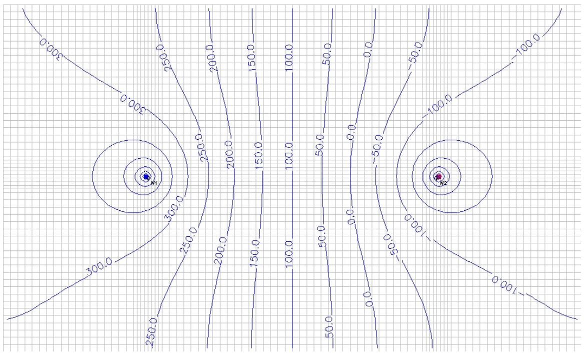

Figure 1: Hydraulic head distribution in the flow model (1 injection and 1 production well, Q=50 l/s).).

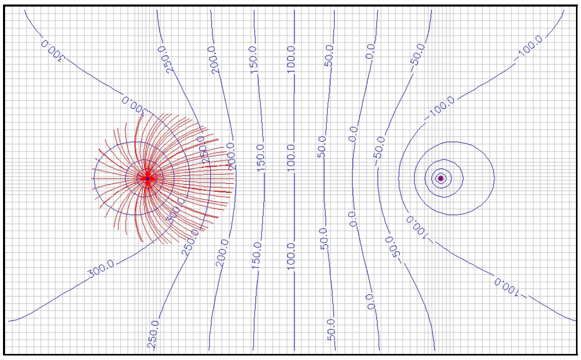

Figure 2: Position of the path-lines from the injection well after 20-day simulation in the flow model (1 injection and 1 production well, Q=50 l/s).

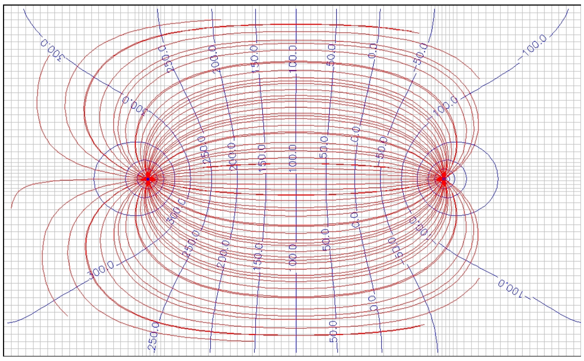

Figure 3: Position of the path-lines from the injection well after 365-day-long simulation in the flow model (1 injection and 1 production well, Q=50 l/s).

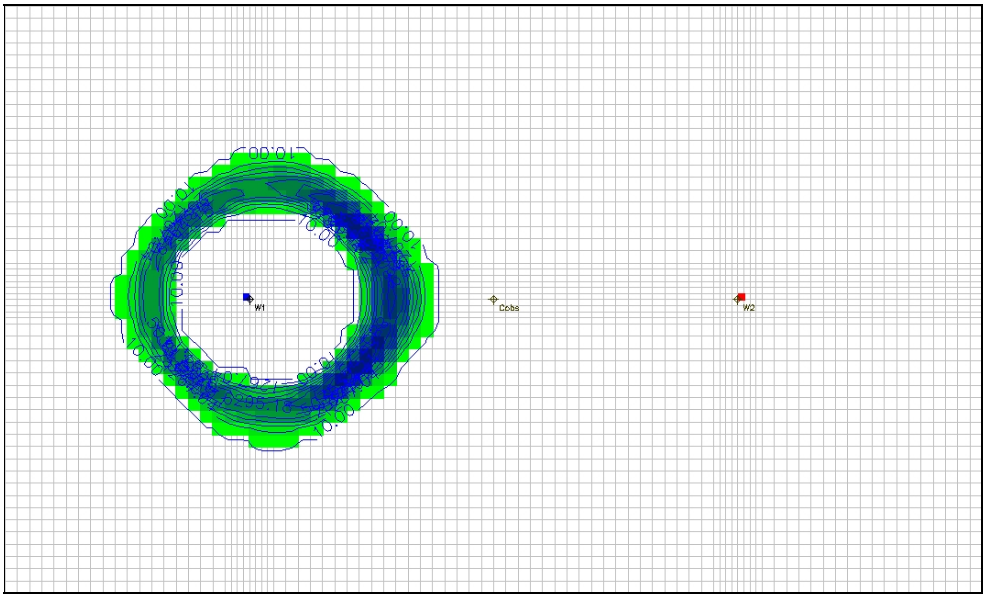

Figure 4: Position of the injected tracer plume with a concentration higher than 10 $\mu g/l$ in the transport model after 20 days.

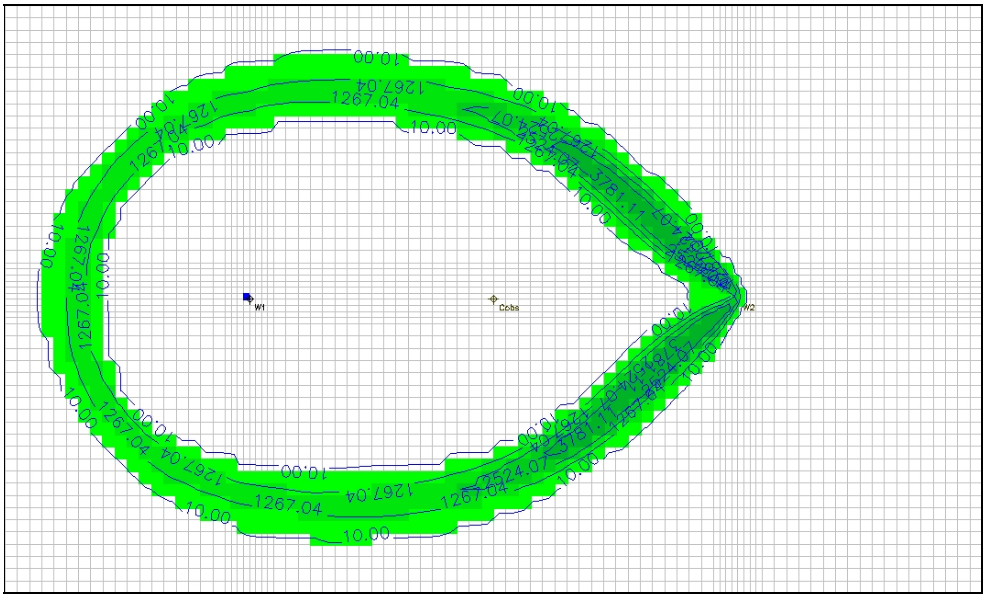

Figure 5: Position of the injected tracer plume with a concentration higher than $10\ \mu g/l$ in the transport model after 100 days.

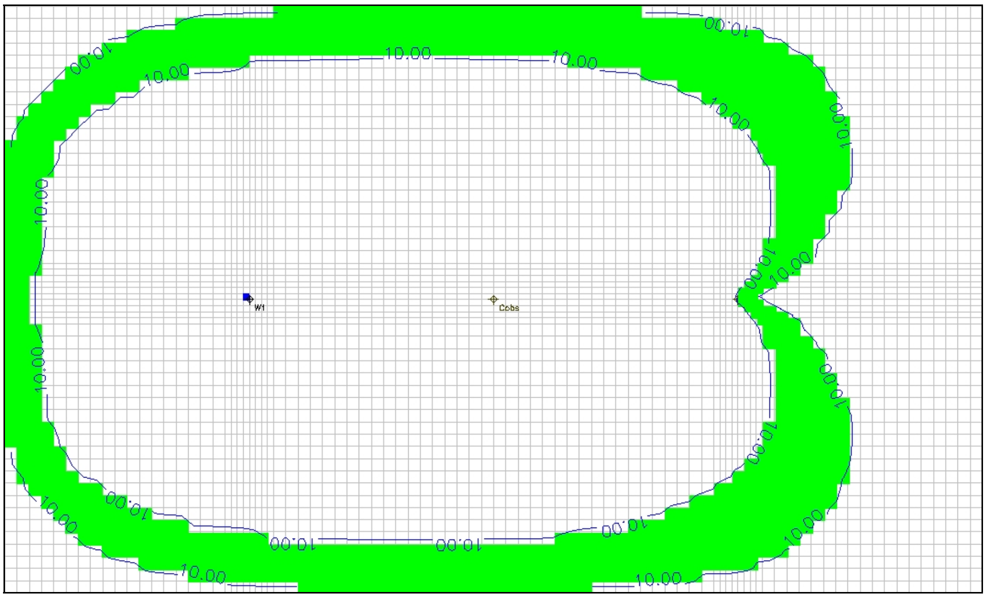

Figure 6: Position of the injected tracer plume with a concentration higher than $10\ \mu g/l$ in the transport model after 360 days.