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MODELLING GROUNDWATER PUMPING AND COUPLED HEAT TRANSPORT IN A ALLUVIAL AQUIFER: TESTS USING DIFFERENT CODES AND OPTIMISATION

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Summary. Various aquifers are studied in terms of low temperature geothermal potential. The feasibility and impact studies of these systems imply very often a numerical simulation of groundwater flow and heat transport. Nowadays, some finite element or finite difference codes are able to deal with such non linear simulations. On a synthetic case study and then on a real case study, a detailed comparative sensitivity analysis is performed using three different codes (MT3DMS, SHEMAT and HYDROGEOSHERE). For low temperatures and relatively small temperature changes, it appears rapidly that the uncertainty affecting values of the main hydrodynamic parameters (i.e. hydraulic conductivity) influences more the results than taking into account any coupling or non linearity. For a case study, the pumping and associated groundwater flow and heat transport are modeled in an alluvial aquifer interacting with a main river in order to assess feasibility of a low energy air cooling /heating system for a large office building. The worst case scenario corresponds to hot summer conditions simultaneously with river maximum temperature and the model leads to an optimization with intermittent pumping in minimum 6 wells. Numerical codes are ready to simulate complex groundwater flow, solute transport and heat transport situations in aquifers, however efforts must be realized to obtain reliable experimental in-situ measured values for the hydro-thermal properties.

1 INTRODUCTION AND CASE STUDY CONTEXT

Two kinds of systems are currently investigated for very low enthalpy geothermal systems: (a) in highly permeable geological formations, groundwater can be pumped to the surface[1]; (b) in low permeability or unsaturated media, groundwater can not be exploited in sufficient amount, geothermal probes (or Boreholes Heat Exchangers) can be installed[2]. In the first case, an open loop system uses groundwater directly in the heat exchanger and then discharges it into another far-away well or into a surface water body. It is thus important to develop computation and modeling tools for assessing the hydrogeological feasibility of such a system. In our case study, aiming to assess the feasibility of heating and air cooling system for a large office building by groundwater pumping, it was particularly important to simulate the pumping effects in terms of drawdown but also in terms of heat transport in the alluvial aquifer of the river Meuse (Belgium). An important volume of pumped groundwater is required at a given temperature of 12°C. Given the local hydrogeological conditions, it can be expected that the induced drawdown could actually inverse the normal hydraulic gradient towards the river, leading in summer to a heat contamination of the pumping wells by warm water flowing through the aquifer from the river. In the summer period, the temperature of the river can actually reach 25°C, corresponding to the worst case scenario considered by the planners of the project.

2 HEAT TRANSFER ASSOCIATED TO GROUNDWATER FLOW

Considering the equality (thermal equilibrium) of the temperature between the fluid and the rock matrix and assuming that convection is mainly governed by the pressure gradient[3], the balance equation of heat transfer in a saturated porous medium in transient conditions can be written as following:

$$\left(\frac{\rho_m\, c_m}{n_e\, \rho_w\, c_w}\right) n_e \frac{\partial T}{\partial t} = \overrightarrow{div}\left[n_e\left(\frac{\lambda_m}{n_e\, \rho_w\, c_w} + \mathbf{D}\right)\overrightarrow{grad}\, T\right] - \overrightarrow{div}\left(n_e\, \overrightarrow{v_e}\, T\right) + \frac{q'}{\rho_w\, c_w} \qquad (1)$$

where T the temperature of the fluid in the porous medium is the main variable, ρ_m is the volumic mass of the saturated porous medium, c_m the specific heat capacity of the saturated porous medium, n_e the effective porosity of the medium, ρ_w the volumic mass of water, c_w the specific heat capacity of water, λ_m the thermal conductivity of the porous medium, **D** the tensor of thermo-mechanical dispersion, v_e the effective velocity of groundwater (function of the hydraulic conductivity and the inverse of effective porosity), and q' is the source/sink term.

The thermal conductivity and the specific heat capacity of the porous medium are increasing with the water saturation of the porous medium. The hydraulic conductivity and the effective porosity are the key parameters for convection because they influence strongly the groundwater effective velocity. The third way of transferring heat in the aquifer is the total effective thermo-mechanical dispersion including thermal diffusion and thermo-mechanical dispersion. The longitudinal and transversal thermo-mechanical dispersivity coefficients are highly dependent on the considered scale as it is the case for the solute transport dispersivity coefficients. The heat transport equation is similar to the mass balance equation of solute transport for an ideal tracer:

$$R\, n_e \frac{\partial C^v}{\partial t} = \overrightarrow{div}\left[n_e\left(\mathbf{D_h}\, \overrightarrow{grad}\, C^v - \overrightarrow{v_e}\, C^v\right)\right] + C^v q' - n_e\, \lambda\, C^v\, R \qquad (2)$$

where C^v the volumic concentration of solute is the main variable, R is the retardation factor, n_e the effective porosity, $\mathbf{D_h}$ the hydrodynamic dispersion, v_e is the effective velocity of groundwater, λ the linear degradation coefficient, and q' is the source/sink term.

By comparing these two equations term by term, it is possible to compute heat transfer using a classical code solving solute transport with equivalent values chosen for the different parameters[4,5]. However, the thermal conductivity and the specific heat capacity are function of the temperature[11,17,18]. This variation can be taken into account using empirical relations provided by the literature in thermodynamics. Hydraulic conductivity can also vary in function of temperature through the water characteristics (essentially dynamic viscosity). Heat transport is influenced by the groundwater flow (i.e. groundwater effective velocity) and vice-versa. Using classical solute transport codes such as MT3DMS[6] for solving the heat transfer equation with constant parameters is thus only an approximation of a more complex situation.

3 RESULTS COMPARISON ON A SYNTHETIC CASE

For a given synthetic case, results obtained with three codes, MODFLOW2000[7] + MT3DMS, HydroGeoSphere[8,9,10] (HGS) and SHEMAT[11] are compared for assessing the importance of coupling and non linearity effects of the main parameters due to temperature evolution. As mentioned previously, MT3DMS solves the heat transfer with constant parameters by using the complete analogy with the solute transport equation. HGS can solve specifically the heat transport equation but with constant parameters. SHEMAT on the contrary can take into account the parameters non linearities due to the temperature effect.

The chosen synthetic model describes a rectangular zone (Fig. 1) and is parameterized to reproduce a typical alluvial aquifer. For groundwater flow, a third type Fourier boundary condition is prescribed on the southern boundary to simulate the interaction with a river (without prescribing the water flux direction). Prescribed heads are chosen on the eastern and western boundaries and a limited prescribed input flux on the northern boundary corresponding to lateral recharge from the hill slope. Groundwater pumping is simulated inducing water leakage from the river towards the alluvial aquifer. Temperatures of groundwater and river water are assumed to be respectively equal to 12°C and 25°C.

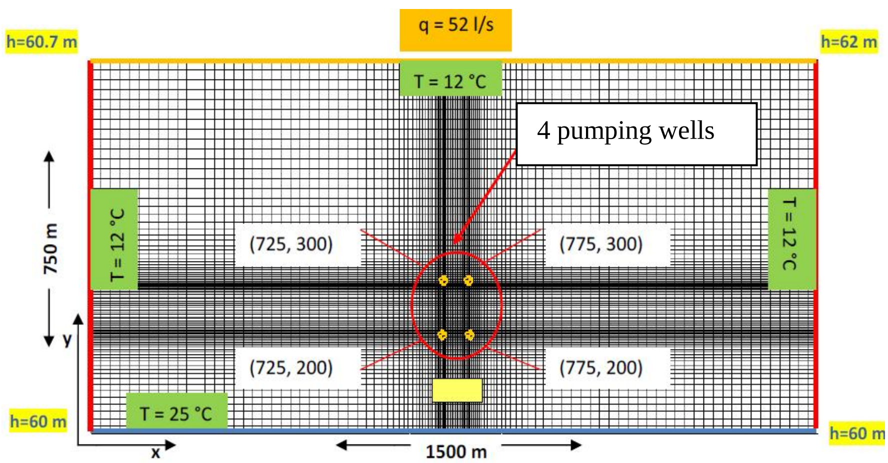

Figure 1: Conceptual choices for the synthetic test case: mesh grid and boundary conditions.

The evolution of the heat plume is modeled with both codes. An example of results is given in figure 2 showing no significant difference and confirming that the approximation made with constant parameters is valid for this range of temperature. This result was not surprising given the limited influence on the parameters for relatively small changes in temperature, but more generally this kind of synthetic test cases can be used for checking if the chosen assumptions are appropriate.

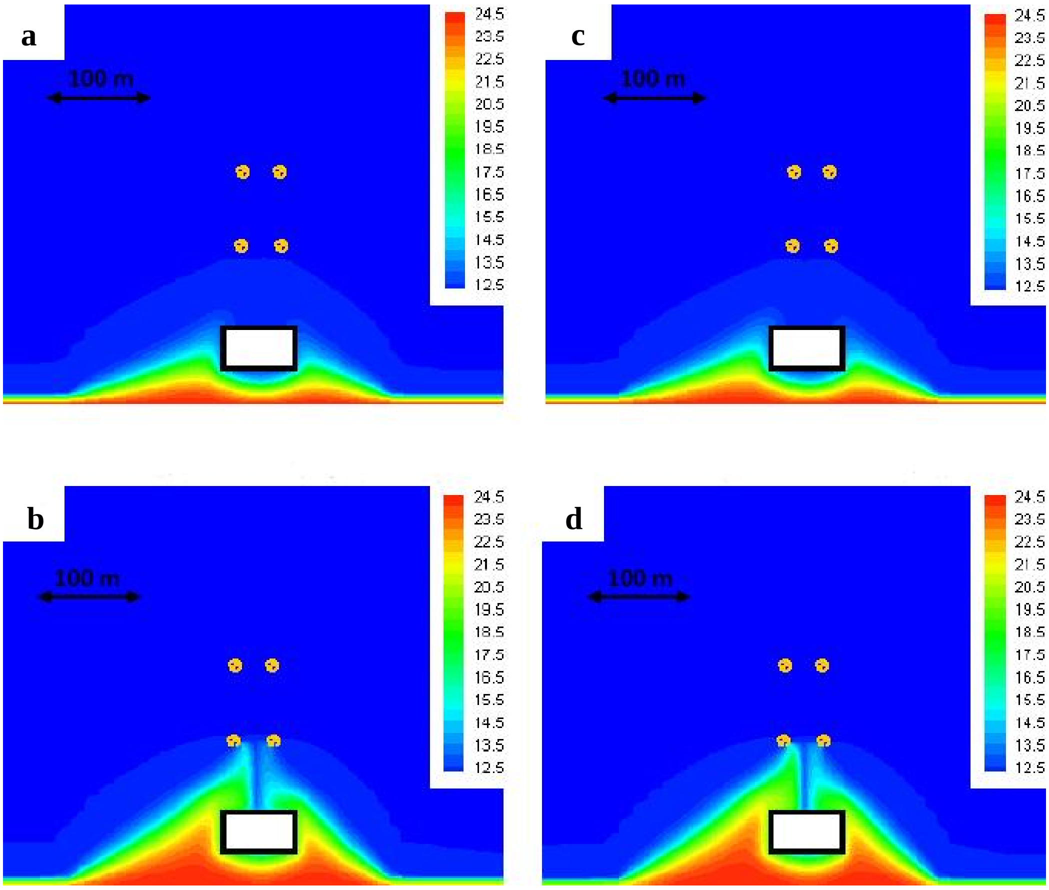

Figure 2: Synthetic test case, computed temperature by MT3D respectively after 3 days (a) and 1 week (b) of pumping; and by SHEMAT respectively after 3 days (c) and 1 week (d) of pumping (temperatures in °C).

4 CASE STUDY

Based on observations from the synthetic model, we used a constant parameter approach was chosen using the HGS code. This choice is justified by the use in this code of a specific capacity attributed to the node centered vertical line representing each well in the quadrangular finite elements mesh[12]. This feature provides more accurate and realistic results in the zones nearby the pumping wells.

The aim was to develop a modeling tool for assessing the feasibility of a low energy cooling/heating system for a large office that will be located in the alluvial plain of the river at a distance of about 130 m from the river. Former hydrogeological studies in the alluvial aquifer have evidenced a wide range of hydraulic conductivities[13, 14, 15] ranging from 2.10^{-4} to $7.5\ 10^{-4}$ m/s. More detailed information and data on that case study have been published separately[16] and are very similar to those tested in the synthetical case. Due to the high urbanization, direct infiltration recharge to the aquifer is supposed to be negligible. In terms of heat transfer, the initial groundwater temperature is supposed to be equal to 12°C. The temperature of the water in the river is chosen equal to 25°C corresponding to extreme warm conditions. Two layers have been considered in the model, one for loams and locally for backfill materials, the second for sands and gravels. Without any local measurements of the thermal properties in the alluvial sediments, values from a study located in similar loamy sands and gravels in Nagaoka[17] were adopted.

As observed in the synthetic case, it is expected that the pumping could actually inverse locally the main hydraulic gradient going to the river, inducing a heat contamination of the pumping wells by warmer water coming from the river. Different scenarios of pumping have been modeled, (1) continuous pumping and (2) intermittent pumping from 8 am to 8 pm, 7 days per week. For these two scenarios, in a first step, the well location has been optimized to maximize the pumping rate keeping the drawdown lower than 1 m outside the plot property of the owner group. In figure 3, the spatial distribution of temperature in the aquifer after 1 month and 3 months of continuous pumping is presented. It can be clearly seen that the heat plume coming from the river reaches some of the pumping wells. For this configuration of pumping, the temperature of the groundwater becomes too high for the cooling system.

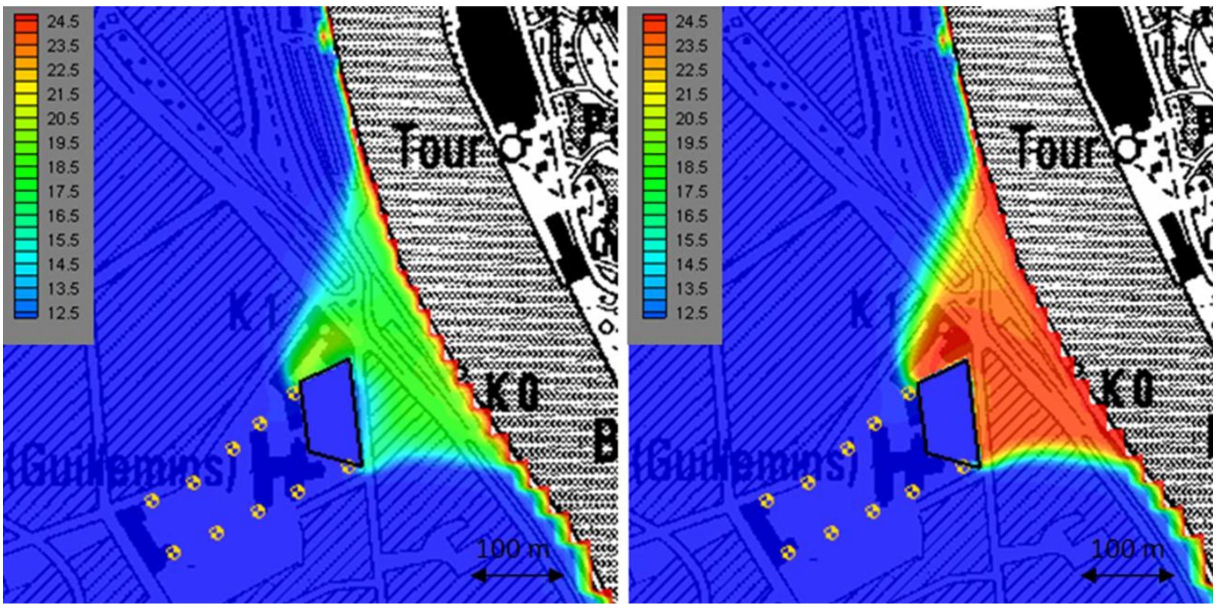

Figure 3: Computed temperature in the aquifer after 1 month and 3 months of continuous pumping (20 m³/h) in each of the 10 wells (temperatures in °C).

As the cooling is mainly required during the office opening hours, intermittent pumping from 8 am to 8 pm has been investigated. In Figure 4, the modeled maximum drawdown and the computed spatial distribution of temperature in the aquifer after 1 month of intermittent pumping are presented. It can be clearly seen that the heat plume coming from the river do not reach any more the pumping wells. For this configuration of pumping, the extent of the heat plume remains limited and located near the river.

The model has allowed performing a sensitivity analysis to identify the key-parameters influencing the computed heat transfer results of the model. As expected, it confirmed that the most influent parameter is the hydraulic conductivity of the sands and gravels of the alluvial aquifer. Consequently, it has been strongly advised to the project manager to perform detailed pumping tests in order to assess more reliable and local hydraulic conductivity values.

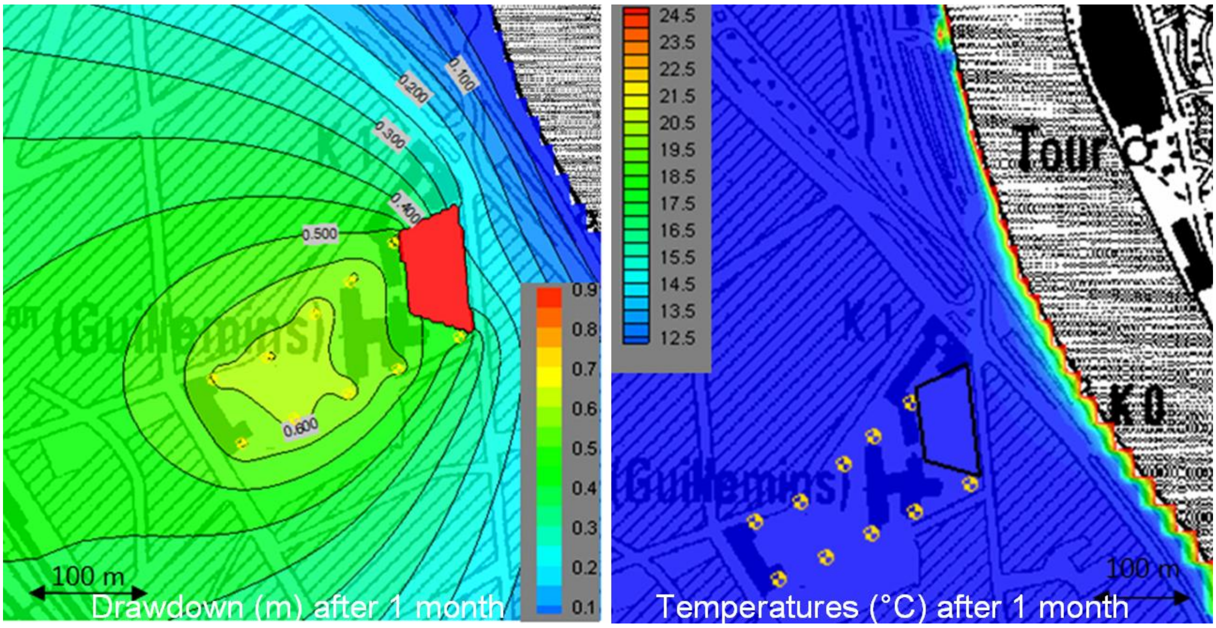

Figure 4: Computed maximum drawdown (left) and computed spatial distribution of the temperature (right) in the aquifer after 1 month of intermittent pumping (drawdown in m, temperature in °C).

5 CONCLUSIONS

Conventional solute transport codes can be applied to model heat transfer in groundwater for very low temperature ranges taking benefits of the similarity between solute transport and heat transfer equations. The applicability of these codes using constant parameters has been satisfactory tested by comparing their results with a coupled/non linear code that take into account the influence of the variation of the temperature on the parameters.

Using HGS[8], a groundwater model has been implemented for a case-study in the alluvial plain of the Meuse river in order to provide an integrated tool for assessing the feasibility of a low energy cooling/heating system for a large office building. Optimized locations of the pumping wells and pumping schemes have been defined. An added value comes from the sensitivity analysis showing that the hydraulic conductivity is the most sensitive parameter of the model. It allowed advising detailed field tests such as pumping tests to determine more accurately hydraulic conductivity values. The computation codes are ready to simulate really complex groundwater flow, solute transport and heat transport situations in aquifers, however it is remarkable that relatively few experimental values of the hydro-thermal properties are available in the literature. As mentioned previously[18], ‘although heat-flow theory has been influential in the development of the theory of groundwater flow, interest in using temperature measurements themselves in groundwater investigations has been sporadic’. Efforts must be realized in that direction to improve the reliability of further computations aiming to optimize very low temperature geothermal systems.

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