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NUMERICAL SIMULATION OF HEAT TRANSFER ASSOCIATED WITH LOW ENTHALPY GEOTHERMAL PUMPING IN AN ALLUVIAL AQUIFER

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(7 figures, 2 tables)

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ABSTRACT. In a context favourable to renewable energies, various aquifers are studied to supply heating and/or cooling systems. The groundwater flow and heat transport are modelled in the alluvial aquifer of the river Meuse in providing an integrated tool for assessing the feasibility of a low energy air cooling/heating system for a large office building by pumping groundwater and discharging it in the river after being heated/cooled by using heat pumps. First, a comparative sensitivity analysis is performed using different codes for assessing the influence of coupling and non linearities on the main parameters due to the temperature evolution in function of time. Then, assuming that the aquifer temperature variation is weak enough to neglect its influence on hydrodynamics and thermal parameters, the MT3DMS and HydroGeoSphere codes are used for modelling the actual case-study. In practice, the worst case scenario considered by the project manager is the cooling of the office building during the hottest summer conditions. So, the influence of the warm water from the river Meuse is computed as it constitutes the major limiting factor. An optimisation of the pumping schema is computed to maximise the efficiency of the system.

KEYWORDS. Low energy geothermy, pumping, modelling, heat transport, groundwater, alluvial aquifer, renewable energy, georesources.

1. Introduction

Nowadays, opportunities are presented for innovative, more efficient approaches for energy and water use to meet global energy and water needs. Especially in the building sector, efficient design and construction of energy efficient buildings for the future become priorities. Geothermal systems can be part of these new renewable available energy resources with the advantage on wind power or solar energy that they are not dependent on the highly variable meteorological conditions.

Geothermal energy consists traditionally in the exploitation of the earth heat. In the underground, temperature increases on average between 18°C and 20°C per kilometre of depth, and a larger geothermal gradient can be found in many places (Skinner et al., 2004). Geothermal systems can be classified into low energy (associated with low depth) or high energy systems (in many cases associated with high depth). High energy systems can be developed by pumping directly the hot geofluid in one well and injecting the cooled geofluid in another well, using a heat exchanger at the surface that vaporises a working fluid used to turn an electricity-generating turbine (Wood, 2009). Low energy systems, for which the ground temperature is too low to produce electricity are generally developed using heat pumps to produce directly heat. On the contrary, in the summer, the relatively low temperature of the low depth underground can be used for cooling and air conditioning.

Two kinds of systems are currently investigated for low (or very low) energy systems: (a) in highly permeable geological formations, groundwater can be pumped to the surface (Castello, 2004); (b) in low permeability or unsaturated media, groundwater can not be exploited in sufficient amount, geothermal probes (or Boreholes Heat Exchangers) can be installed (Gehlin, 2002). In the former case, an open loop system uses groundwater directly in the heat exchanger and then discharges it into another far-away well, into a stream or lake, depending upon local regulation and environment conditions. In the last case, a coolant fluid is circulated in the probes to extract the underground heat. A closed loop of pipe, placed either horizontally (1 to 2 m deep) or vertically (50 to 100 m deep, Borehole Thermal Energy Storage - BTES), is placed in the ground. A coolant fluid is circulated through the plastic pipes to either collect heat from the ground in the winter or reject heat to the ground in the summer.

All these systems must be optimised in relation with the most adequate ground source heat pump system to be designed in accordance with the local geological and hydrogeological conditions. The development of such systems requires estimating the heat fluxes that can be injected or extracted from the underground. It is thus important to develop computation and modelling tools for assessing the hydrogeological feasibility of such systems.

In this work aiming to assess the feasibility of heating and air cooling system for a large office building by pumping the groundwater (open loop system), 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. An important volume of pumped groundwater (200 m^3/h in the main scenario) is required at a given temperature of 12°C. Groundwater flow and heat transport are modelled in the alluvial aquifer of the river Meuse in order to simulate the pumping effect on piezometric levels and groundwater temperature. Especially, the induced drawdown could actually inverse the normal hydraulic gradient towards the river Meuse, leading in summer to a heat contamination of the pumping wells by warm water flowing through the aquifer from the river Meuse. In the summer period, the temperature of the river can actually reach 25°C. This last case has been considered by the planners of the project as the worst case scenario.

2. Equation describing heat transfer in porous saturated media

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 (Pantakar, 1980), the balance equation of heat transfer in a saturated porous medium in transient conditions can be written as following:

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

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 effective 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 (λ_m) and the specific heat capacity (c_m) of the porous medium are respectively the main parameters for heat conduction (first term in the right hand side of equation 1) and the solid-fluid heat transfer (temporal derivative term in the left hand side of equation 1). The hydraulic conductivity (K) and the effective porosity (n_e) are the key parameters for convection because they influence strongly the groundwater effective velocity (v_e). 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:

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

where C^v the volumic concentration of solute is the main variable, R is the retardation factor, n_e the effective porosity of the medium, 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 appears that it is possible to compute heat transfer using a classical code solving solute transport. Using equivalent values for the different parameters allows using the solute transport equation to solve the heat transfer problem in groundwater (Méndez, 2008 ; Fossoul, 2009). However, the thermal conductivity (λ_m) and the specific heat capacity (c_m) are function of the temperature. This variation can be taken into account using empirical relations provided by the literature in thermodynamics. The hydraulic conductivity can also vary in function of temperature through the parameters of the water (essentially the water dynamic viscosity). So, in a non isothermal problem, which is surely the case here, all those parameters induce non linearities in the equation (1) to be solved. The evolution of hydraulic conductivity, thermal conductivity and heat capacity for few different temperatures is shown in Table 1 .

Heat transport is influenced by the groundwater flow (i.e. groundwater effective velocity). Groundwater flow can be also dependent on the heat transfer through the dependence of hydraulic conductivity on the temperature. For accurate simulations, these two processes must normally be coupled in the software. It means that results from the groundwater flow calculation should be used directly by the heat transfer computation and vice-versa, iteratively before any results production for the considered time step.

Using classical solute transport codes such as MT3DMS (Zheng & Wang, 1999) to solve the heat transfer equation is thus only an approximation of a more complex situation where many non linearities can affect values of the thermal and hydrodynamic parameters in function of the reached groundwater temperature

3. Synthetic model

A synthetic model has been developed for assessing the importance of coupling and non linearities in the main parameters due to the temperature evolution in function of time. The results obtained with three codes, MODFLOW2000 (Harbaugh et al., 2000) + MT3DMS, HydroGeoSphere (HGS) (Therrien et al., 2005; Jones, 2005; Sudicky et al., 2008; Goderniaux et al., 2009) and SHEMAT (Clauser, 2003) are compared. MT3DMS solves the heat transfer by using the complete analogy with the solute transport equation: it does not take into account the non-linearity resulting from the evolution of the values of the parameters. HGS can solve specifically the heat transport equation with constant parameters. SHEMAT on the contrary is a code developed specifically for heat transfer. High temperature problems can be

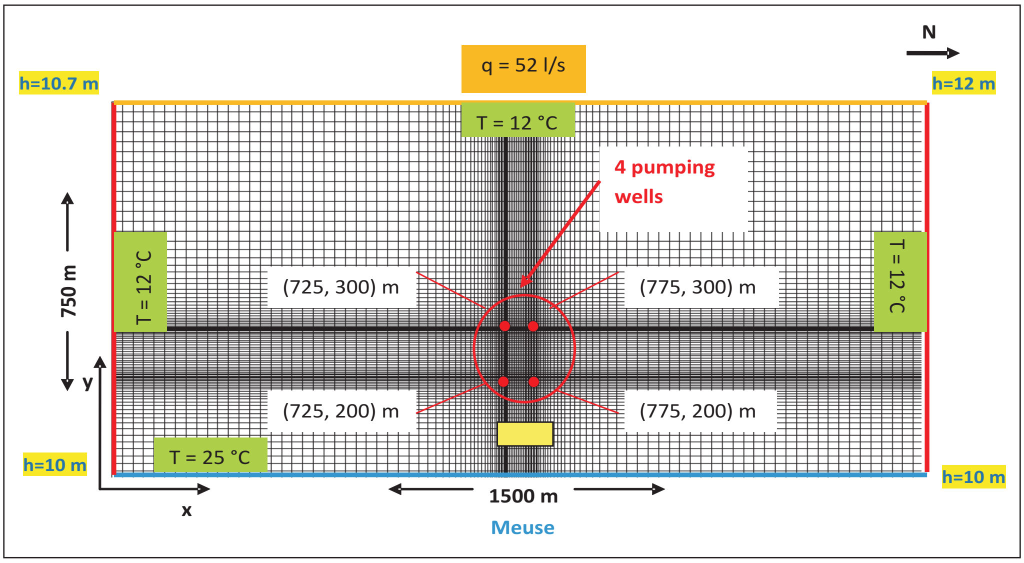

Figure 1. Synthetic test case for groundwater and heat transfer computation: mesh grid and boundary conditions (In red: prescribed head boundary; in orange: specified flux boundary; in blue: the river Meuse ; the yellow rectangle represents the building foundations). The zero level matches with the base level of the model.

handled with this code taking into account the parameters non linearities.

The synthetic model describes a rectangular zone (Fig. 1) and is parameterised to reproduce a typical alluvial aquifer. For the groundwater flow problem, a third type Fourier (or mixed) boundary condition is prescribed on the eastern boundary to simulate the interaction with a river (without prescribing the water flux direction between the river and the groundwater). However due to the high conductance of the riverbanks, they do not represented a real barrier to the groundwater flow. So a prescribed head boundary condition is finally computed as this choice is safer in terms of heat contamination from the river (Fossoul, 2009). Prescribed heads are chosen on the northern and southern boundaries (linear interpolation between the corner values indicated on Fig. 1) and a

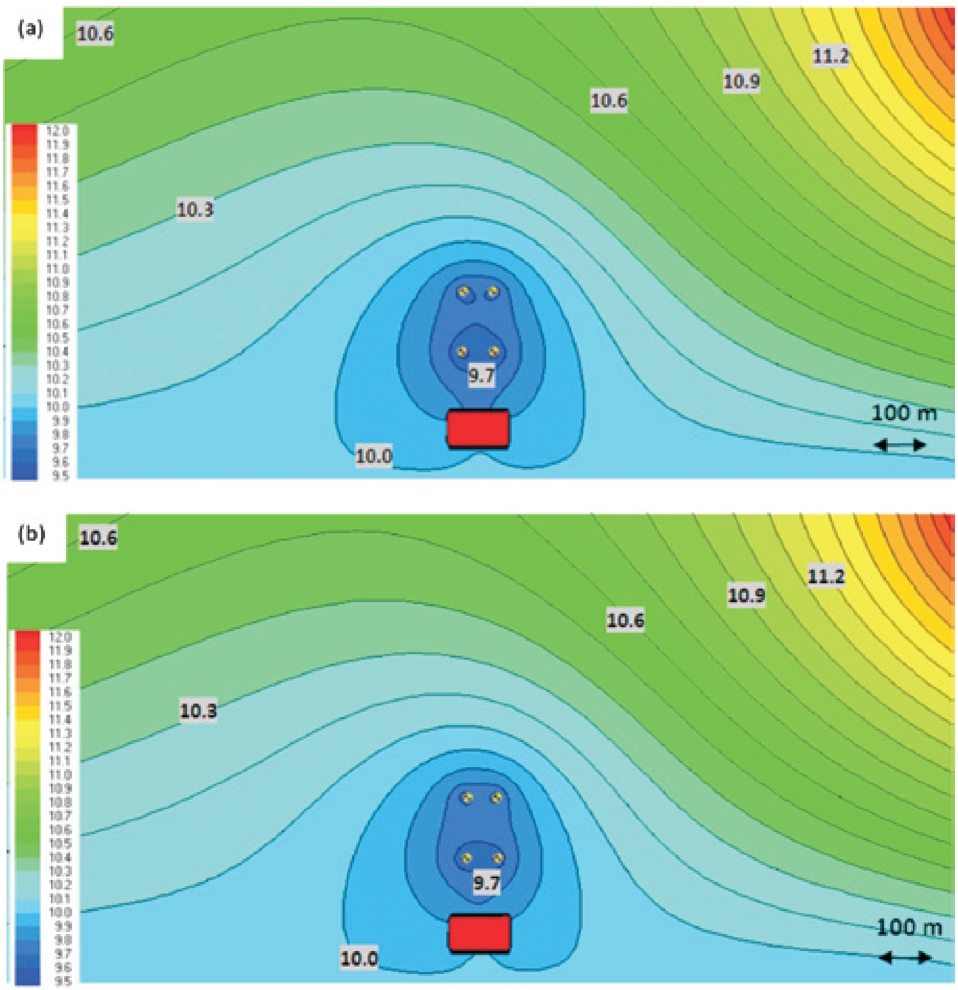

Figure 2. Synthetic test case, computed stabilized piezometric heads due to the pumping: (a) SHEMAT results without coupling with the temperature (constant parameters taken for a 12°C temperature); (b) SHEMAT results with coupling with the temperature (non linear parameters) (heads in meters).

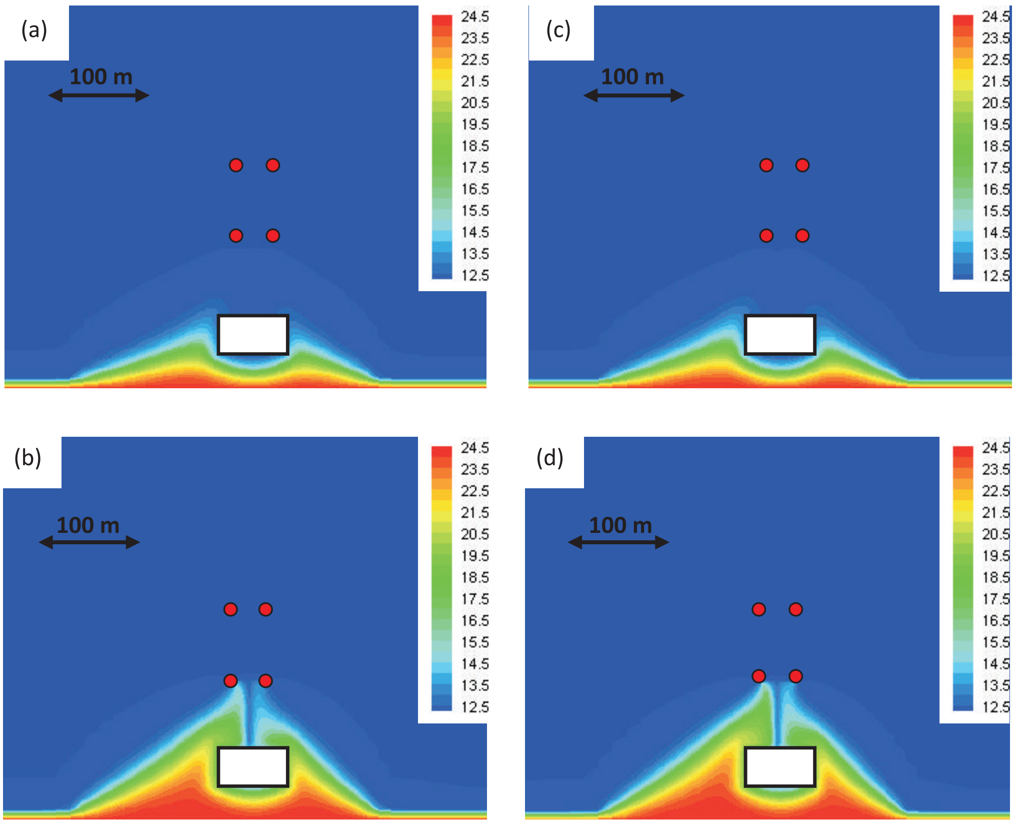

Figure 3. Synthetic test case, computed temperatures : (a) and (b) SHEMAT results without coupling with the temperature respectively after 3 days and 1 week of pumping ; (c) and (d) SHEMAT results with coupling with the temperature respectively after 3 days and 1 week of pumping (temperatures in °C).

limited prescribed flux (total flux of 52.2 l/s) on the western boundary corresponding to a lateral feeding of the alluvial aquifer from infiltration in a neighbouring hillslope. This flux has been calculated from a previous computation of the natural groundwater flow where a prescribed head boundary condition was used, allowing to estimate the flux passing through the boundary (Fossoul, 2009). Groundwater is pumped out of the model at a high pumping rate (300 m^3/h) in order to induce a feeding of the aquifer by the river and thus an important heat plume in the aquifer. The temperatures of the groundwater and of the water in the river are assumed to be respectively equal to 12°C and 25°C. The stabilised heads computed by the 3 codes have been compared and the results are nearly identical (Fossoul, 2009). Then the results obtained with SHEMAT will be the only presented as they are the most useful to assess the influence of coupling and non linearities. The groundwater flow and evolution of the heat plume is modelled with SHEMAT, first assuming the linearity of the parameters and then taking into account their non linearities (Figs 2 and 3). The results are very close to each other confirming that the approximation of 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.

4. Case study

Based on observations from the synthetic model, a groundwater flow and heat transfer model has been developed for the considered study case. The aim was to develop a modelling tool for assessing the feasibility of the low energy air cooling/heating system for a new large office that will be situated in Liège in the alluvial plain of the river Meuse at a distance of about 130 m from the river. We used on one hand the classical MODFLOW2000+MT3DMS codes and on the other hand the HGS code with the same meshing grid. All results have been produced using both methods. It turned out that all simulation results were found very similar. Consequently, only results produced by HGS will be showed in the following. This choice is justified by a better simulation of the pumping wells in HGS due to the use of a specific capacity attributed to the node centred vertical line representing each well in the quadrangular finite elements mesh (Therrien & Sudicky, 2001). This improvement has implications for the correct modelling of contaminant/heat transport to the well. It is not within the scope of this work to describe further respective advantages and disadvantages of each code.

The studied zone is located in the alluvial plain on the left bank of the river Meuse near the railway station in Liège (Belgium). The water level of the river Meuse is artificially controlled by dams in Ivoz-Ramet and Monsin respectively located upstream and downstream of the site: it can be considered in the model as equal to 59 m corresponding to typical situations of the 'worst case' scenario. As mentioned previously, this worst case scenario corresponds to a summer period requiring a maximum pumping of the alluvial aquifer together with a maximum temperature in the river Meuse reaching 25°C.

The alluvial aquifer of the river Meuse is mainly

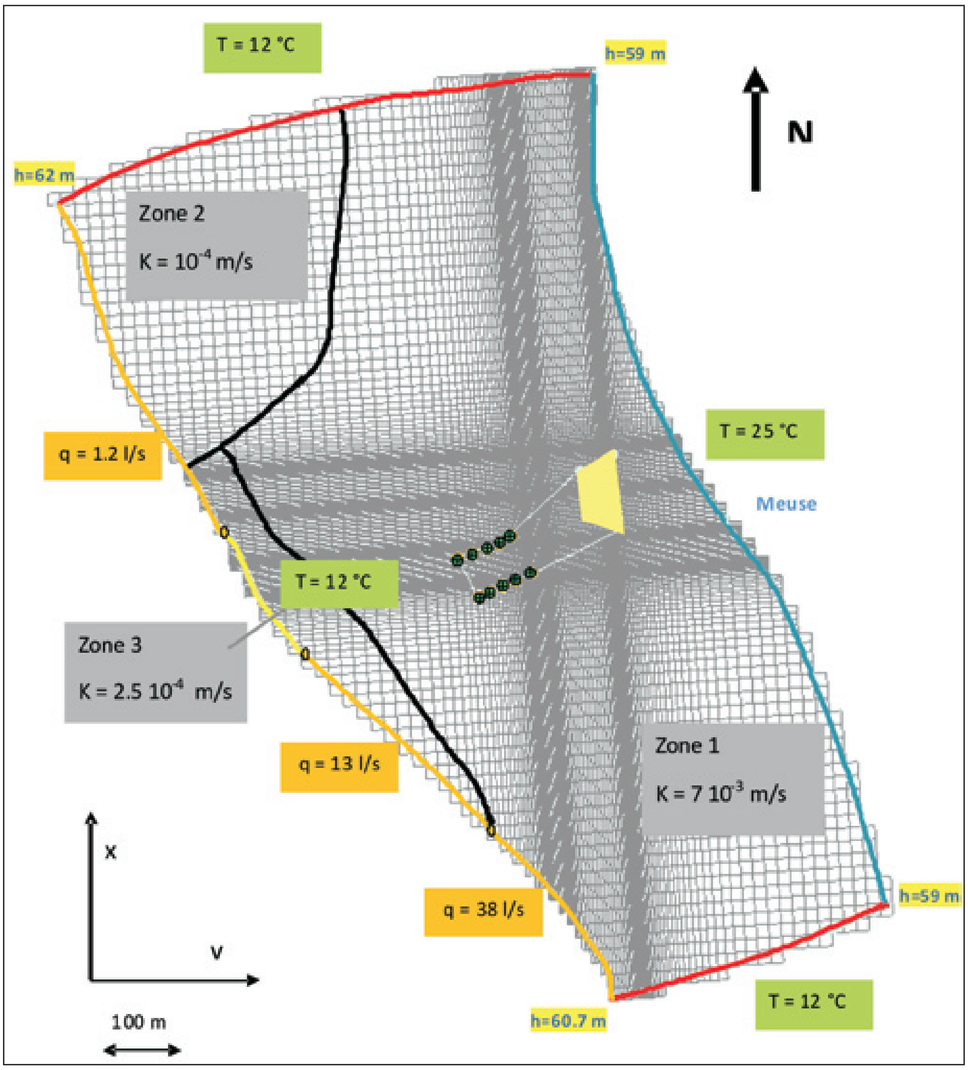

Figure 4. Case study groundwater model: grid mesh, boundary conditions (in red: prescribed head boundary; in orange: specified flux boundary; in yellow: impermeable boundary; in blue: the river Meuse), office building foundations (yellow polygon), and initial pumping wells layout (10 points).

composed of loamy sands and gravels.

From top to bottom, the geological setting is made up of:

- locally several meters of backfill materials;
- fluviatile loams with a thickness ranging from 0 to 6 m;
- fluviatile sands and gravels from 2 to 10 m thick;
- shales, sandstones with coal intercalations from the Coal Measures Group (Carboniferous).

Former hydrogeological studies in the alluvial aquifer have evidenced a wide range of hydraulic conductivities ranging from 2.10^{-4} to $7.5\ 10^{-4}$ m/s (Dassargues, 1991; Derouane & Dassargues, 1998; Brouyère, 2001; Peeters et al., 2004; Battle-Aguilar, 2008; Battle-Aguilar et al., 2009). Locally, only little information is available. Measured groundwater levels obtained from the geotechnical map (Fagnoul et al., 1977) range from 62 m near the hillslope to 59.5 m near the river, showing a groundwater flow toward the Meuse with a low hydraulic gradient around 2 to 4 ‰.

Although the site of concern is restricted to a few hundreds squared metres, the limits of the modelled zone (Fig. 4) has been extended to a larger area to avoid the influence of prescribed boundary conditions on the modelling results obtained in the site (Fig. 4). At the eastern boundary between the Meuse and the alluvial aquifer, a third type Fourier boundary condition is assumed to account for the riverbank effect. On the northern and southern boundaries, hydraulic heads are prescribed. On the western boundary, groundwater fluxes are prescribed to take into account the underground fluxes coming from the hill. Due to the high urbanisation, direct infiltration recharge to the aquifer is supposed to be negligible. In terms of heat transfer, the temperature is supposed to be equal to 12°C in the groundwater coming through the northern, western and southern boundaries. The temperature of the water in the Meuse is supposed to be equal to 25°C corresponding to extreme warm conditions.

Two layers have been considered in the model, one for the fluviatile loams and locally for backfill materials, the second for the sands and gravels. In the absence of local measured data, the first layer is considered as homogeneous. In the second layer, only three zones of different hydraulic conductivities have been defined in the model after calibration under natural conditions. 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 (Taniguchi, 1993) are adopted. The effective thermal diffusion coefficient ($\varkappa = \lambda_m/\rho_m.c_m$) is taken homogeneously equal to 5.10^{-7} m²/s

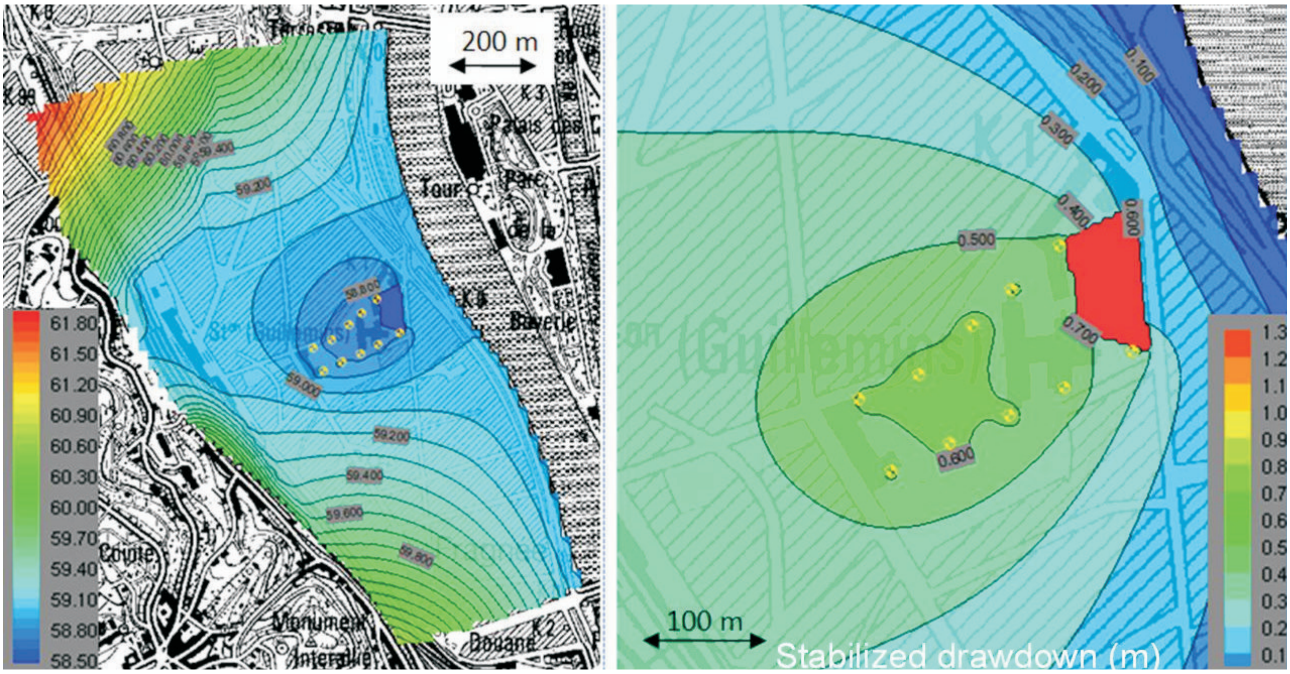

Figure 5. Stabilised piezometric heads and drawdown (zoom on the right) as modelled for a continuous pumping of 20 m³/h in 10 wells (heads and drawdown in meters).

and the thermal conductivity of the saturated porous medium (λ_m) to 1.6 W/m.K. These values are very similar to those obtained in various case studies in porous aquifers. The specific heat capacity (c_m) is chosen (Table 2) from a pilot study in gravels (Urbaneck, 2005). All parameters are assumed constant as their respective variations with temperature remain small with regards to the uncertainty range affecting their value. Similarly, and following the conclusion from the synthetic case described here above, the temperature effect on the hydraulic conductivity is neglected. The effective porosity (n_e) is chosen with a low value corresponding to sandy to loamy gravels of the river Meuse alluvial plain (Brouyère, 2001; Batlle-Aguilar, 2008). If a higher value could be observed in the reality it would induce a smaller groundwater effective velocity, so the computation can be considered as on the security side. The groundwater temperature is considered initially at 12°C. The longitudinal thermo-mechanical dispersivity coefficient is most often taken around a value of 1 meter at that scale of consideration (Mendez, 2008).

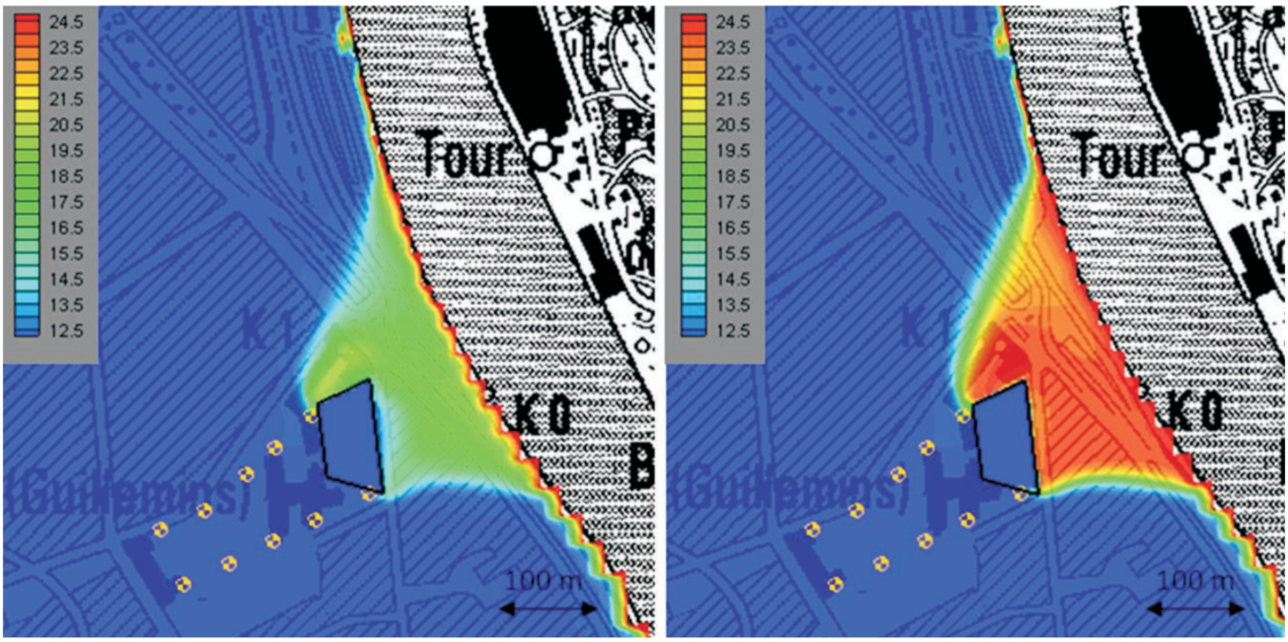

Figure 6. Computed temperature in the aquifer after 1 month and 3 months of continuous pumping of 20 m³/h in 10 wells (temperatures in °C).

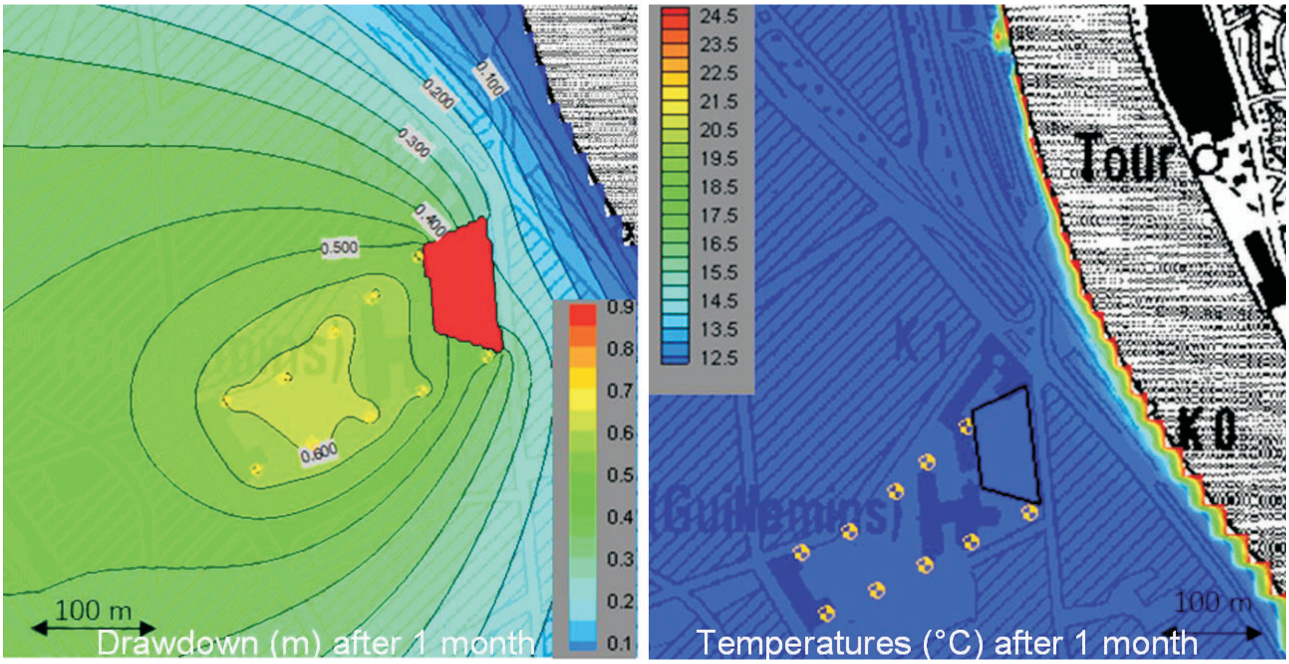

Figure 7. Computed maximum drawdown (left) and computed spatial distribution of the temperature (right) in the aquifer after 1 month of intermittent pumping.

Moreover, the α_{hL}/α_{hT} ratio between the longitudinal and the transversal thermo-mechanical dispersivity coefficients is usually comprised between 3 and 10 for isotropic and homogeneous porous media, here a value of 5 is chosen. The adopted values of the described flow and heat transport parameters are summarised in Table 2. In addition the building foundations reach the top of the bedrock and are supposed to form an impervious barrier. The corresponding cells have thus been deactivated.

The model is designed in the aim of estimating the critical discharge that can be pumped in the aquifer and the associated drawdown for the worst case scenario described above. As observed in the synthetic case, it is expected that the pumping could actually inverse locally the main hydraulic gradient going to the Meuse, inducing a heat contamination of the pumping wells by warmer water coming through the aquifer from the river Meuse. Therefore, the spatial distribution of the pumping wells is chosen in order to be located as far as possible from the river within the plot property of the owner group (Fig. 4).

Different scenarios of pumping have been modelled, (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 wells locations has been optimized to maximize the pumping rate keeping the drawdown lower than 1 meter outside the studied site. In Fig. 5, the stabilised drawdown modelled for a continuous pumping of 20 m^3/h in 10 wells is presented. The spatial distribution of temperature in the aquifer after 1 month and 3 months of continuous pumping is presented in Fig. 6. It can be clearly seen that the heat plume coming from the Meuse reaches some of the pumping wells. For this configuration of pumping, the temperature of the groundwater becomes too high for the cooling system. As the cooling is mainly required during the office opening hours, intermittent pumping from 8 am to 8 pm has been investigated. In Fig. 7, the modelled 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 Meuse 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.

A sensitivity analysis has been performed to identify the key-parameters influencing the computed heat transfer results of the model (Fossoul, 2009). The studied parameters were the hydraulic conductivity, the effective porosity, the specific yield, the thermo-mechanical dispersivity coefficients,the thermal conductivity and the influence of the riverbank conductance. As expected, it confirmed that the most influent parameter is the hydraulic conductivity of the sands and gravels of the alluvial plain. 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.

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 and MT3DMS, a groundwater model has been developed 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 air cooling / heating system for a large office building by pumping the groundwater and discharging it in the river after being heated/cooled by using heat pumps. An optimised location of the pumping wells and the pumping schemes have been defined. The sensitivity analysis performed with the model has shown that the hydraulic conductivity is the most sensitive parameter of the model. It would be thus important to perform detailed field tests such as pumping tests to determine more accurately hydraulic conductivity values as a priority. On the other hand, computation codes are available and ready to be used for simulating groundwater flow, solute transport and heat transport in really complex aquifers, however it is remarkable that relatively few experimental values of the hydro-thermal properties are available in the literature. As mentioned by Anderson (2005), '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 realised in that direction to improve the reliability of further computations aiming to optimise such very low temperature geothermal systems.

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Table 1. Evolution of hydraulic conductivity values, thermal conductivity and heat capacity of the solid for few different temperatures. The values have been calculated from the starting values of the model considered at 12°C (Fossoul, 2009). The variations of K are mainly due to the variations of the water viscosity calculated by a power law (Ewen & Thomas, 1989). The variations of λ_s is calculated by the law of Vosteen & Schellschmidt (2003). An average variation of 2.5 % between 12°C and 25°C is assumed for c_s (Waples, D.W. & Waples, J.S., 2004; Fossoul, 2009). The thermal parameters λ_s and c_s are supposed identical for both types of sediments.

	K (12°C) [m/s]	K (25°C) [m/s]	λ_s (0°C) [W/m.K]	λ_s (12°C) [W/m.K]	λ_s (25°C) [W/m.K]	c_s (12°C) [J/kg.K]	c_s (25°C) [J/kg.K]
Loam and backfill material	10^{-6}	$1.4\ 10^{-6}$	1.95	1.94	1.91	790	810
Sand and gravels	0.005	0.007	1.95	1.94	1.91	790	810

Table 2. Adopted values of the paramaters considered at 12°C in the groundwater flow and heat transport model. ρ_b is the bulk density, D is the effective thermo-mechanical dispersion coefficient of the porous medium.

Saturated gravels		Loams and backfill materials	
K [m/s]	$2.5\ 10^{-4}$-$7\ 10^{-3}$	K [m/s]	10^{-6}
λ_m [W/m.K]	1.6	λ_m [W/m.K]	1.6
c_m [J/kg.K]	1175	c_m [J/kg.K]	1175
ρ_m [kg/m^3]	2200	ρ_m [kg/m^3]	2200
ρ_b [kg/m^3]	1950	ρ_b [kg/m^3]	1950
Porous medium		Groundwater	
n_e [-]	0.05	λ_w [W/m.K]	0.59
D [m^2/s]	10^{-9}	c_w [J/kg.K]	4189
α_{hL} [m]	1	ρ_w [kg/m^3]	1000
α_{hT} [m]	0.2		