Modelling the thermal impact of ground source heat pump systems as a function of hydraulic conductivity

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Abstract

Geothermal heat pump systems are considered to be environmentally-friendly solutions for residential use. The popularity of these systems is expected to rise but the information on their hydrodynamic and thermal impact is scarce. This paper focuses on how the hydraulic conductivity influences the impact on the reservoir caused by a single well-doublet in a shallow geothermal reservoir. The system is able to produce a maximum of 9.44E-04 m^3/s groundwater when installed on a sandy area. Six different strata were defined; the top layer does not take part in water transportation in the original case, but it does have similar features to the lower layers. Scenarios were created to show how the hydraulic effect and the thermal impact change as a function of the hydraulic conductivity of the different layers, while the production was constant. The minimum and maximum values were defined based on the Hungarian conditions.
Keywords: geothermal heat pump system, shallow reservoir, thermal impact, hydrodynamic effect, groundwater modelling, transport model, minimum distance.

1 Introduction

Despite the evident environmental and economic benefits [1, 2] of using low temperature geothermal energy for residential use there are a number of factors that have to be considered. The renewable nature of geothermal resources is function of scale [3] and adverse effects might appear as well [4, 5].

The energy stored in shallow reservoirs may be exploited by either closed or open-loop systems, the latter having greater impact on the environment. In case of an open-loop ground source heat pump (GSHP) system the groundwater serves as the energy source for the heating system directly and it can be either discharged

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into a nearby water body or, as it is the case in Hungary, reinjected to the aquifer by a well or tile field. Beside the potential change in water chemistry the course of flow is likely to alter and thermal impact is unavoidable on both short and long term. These effects on the groundwater quality are not only problematic for the environment but may decrease the efficiency of neighbouring systems.

The hydrodynamic effect, i.e. the Radius of Influence (R_0) can be easily calculated by eqn (1), an empirical equation for unconfined reservoirs based on the work of Sichardt [6]

$$R_0 = 3000 \cdot (H - h_w) \cdot \sqrt{k} \tag{1}$$

where H is the initial head of water table, in m,
h_w is the head in the well during production, in m,
k is the hydraulic conductivity, in m/s.

It has to be noted that the equation calculates with one single layer. An equivalent hydraulic conductivity is calculated from the k values of the different strata. Eqn (1) is commonly used for designing dewatering systems, wells and GSHPs.

Measurements to determine thermal impact can be carried out to a limited extent; therefore modelling approach comes to the forefront. Several works have been carried out to estimate the thermal effects of shallow geothermal systems e.g. [7–9]. The models showed good agreement with experimental data but all three authors pointed out that geographical and seasonal factors influence the thermal characteristics.

In a previous study, Somogyi *et al.* [10] examined a standalone system where a single well-doublet with a maximum capacity of 9.44E-04 m^3/s was installed in a shallow geothermal reservoir. Simulation results showed that the thermal affected zone was 26 m in case of normal operation (2.83E-04 m^3/s) but with an increased production of 7.08E-4 m^3/s the thermal impact rose to 60 m.

In this paper the authors present the results of a new series of simulation to define the complex relationship between the hydraulic conductivity and the hydraulic and thermal impact of the well-doublet.

2 Methods and materials

The model structure is the same as in [10]. The standalone system has six strata (Figure 1), the two wells are 30 m far from each other. Water is pumped from the 6^{th} layer and injected in the 4^{th}. This is a simplification of the real system where the wells are screened into more than one stratum. The nominal heating capacity of the heat pump is 17.1 kW, the annual water demand of the system is 4400 m^3 fully used for energy production. Calibration of the system was carried out by using the drilling log (Table 1) and temperature measurement data.

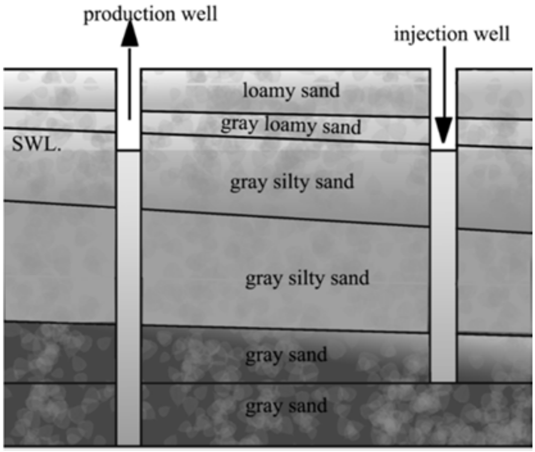

Figure 1: The geological structure of the modelled area [10].

Table 1: Characteristics of the modelled area.

		Calibration		Changed
Number of layer	Depth of bottom (m)	Type	k (m/s)	
1	1.4–2.2	loamy sand	1.50E-06	No
2	2.1–3.2	gray loamy sand	1.50E-06	No
3	5–6.7	gray silty sand	1.89E-06	Yes
4	10–10.5	gray silty sand	1.89E-06	Yes
5	12	gray sand	1.72E-05	Yes
6	15	gray sand	1.72E-05	Yes

Steady state modelling was carried out with Processing MODFLOW 5.3, a freeware [11] for hydrodynamic and transport models. To describe the heat transfer, advection was used as the bulk fluid motion was the dominant process [4].

In order to determine the correlation between hydraulic conductivity and thermal affected zone, four different values were defined based on the classification of Hungarian soils [12]: 4.0E-06 m/s (sandy silt), 1.0E-05 m/s (silty fine sand), 6.0E-05 m/s (fine sand), 1.0E-05 m/s (medium sand). As indicated in Table 1 layer 3 to 6 were assigned with these values. Since the order of the elements count but repetition is allowed the total number of variation was 256. Because the wells were screened to the 4th and 6th layer those cases were omitted in which these strata had lower hydraulic conductivity values than their neighbours. That reduced the number of situations to 85.

In order to determine the effects in cases when the hydraulic conductivities of the layers differ greatly, two additional categories were chosen: 3.0E-04 m/s (coarse sand) and 6.0E-04 m/s (gravelly sand). This time the layers were assigned with a maximum of two different values. Some of the cases with higher k gave back false drawdown results because the conditions would have assumed different initial values, too. Thus only 34 selected cases were selected. A total of 119 simulations for hydraulic and transport models were run for 180 days.

3 Results

For each variant that was chosen the difference between the initial head and the final head in the wells, i.e. the drawdown (Figure 2) or elevation (Figure 3), the hydraulic impact (Figure 4) and the thermal affected zone (Figure 4) were defined. The hydraulic impacts for both the production and the injection well were calculated with eqn (1).

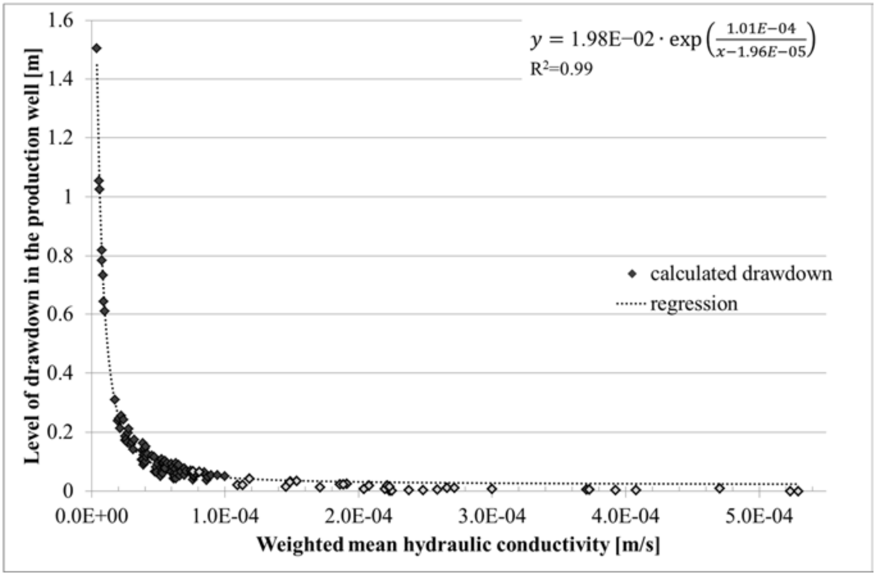

Figure 2: Calculated drawdown of 119 cases as a function of thickness-weighted mean hydraulic conductivity. The white diamonds indicate the second 34 variants.

The levels of drawdown as a function of the thickness-weighted hydraulic conductivity are shown in Figure 2. A modified exponential decay function (eqn (2)) was found to fit the simulation results best in all cases. Parameters a, b and c are either given in the figure or in a separate table.

$$y = a \cdot \exp\left(\frac{b}{x-c}\right) \tag{2}$$

The hydraulic conductivity is directly proportionate to the water budget. As the *k* increases more water is able to move in the system therefore a well produces lesser level of depression. That suggests that the potential interaction between neighbouring boreholes should be examined in systems with smaller hydraulic conductivity.

The same tests have to be carried out with the injection well, too. The estimation of increased height of the water table is particularly important if more than one well is used to reinject the groundwater. The regression analysis gave a correlation coefficient of 0.83 for a single curve. The results showed that the hydraulic conductivity in the 6th layer where the production well is screened had greater impact on the elevation level than the others (Figure 3). The parameters for eqn (2) are given in Table 2. This finding indicates that the average hydraulic conductivity in itself cannot be used to determine how the well-doublet influences the characteristics of the reservoir.

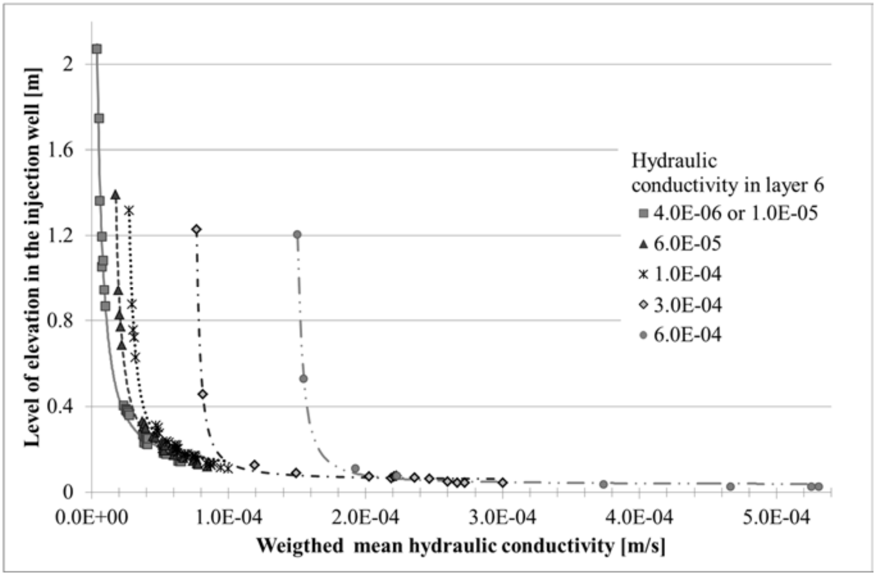

Figure 3: Calculated level of elevation in the injection well in the function of thickness-weighted mean hydraulic conductivity of 119 cases.

Table 2: Parameters for eqn (2) to determine the elevation in the injection well.

	Hydraulic conductivity in layer 6				
	4.0E-06 or 1.0E-05	6.0E-05	1.0E-04	3.0E-04	6.0E-04
a	9.77E-02	1.06E-01	1.00E-1	5.47E-2	3.40E-02
b	4.70E-05	3.26E-05	3.13E-05	3.08E-05	5.49E-05
c	1.13E-05	-5.00E-06	-1.54E-05	-6.68E-05	-1.35E-04
R^2	0.99	0.99	0.99	1.00	1.00

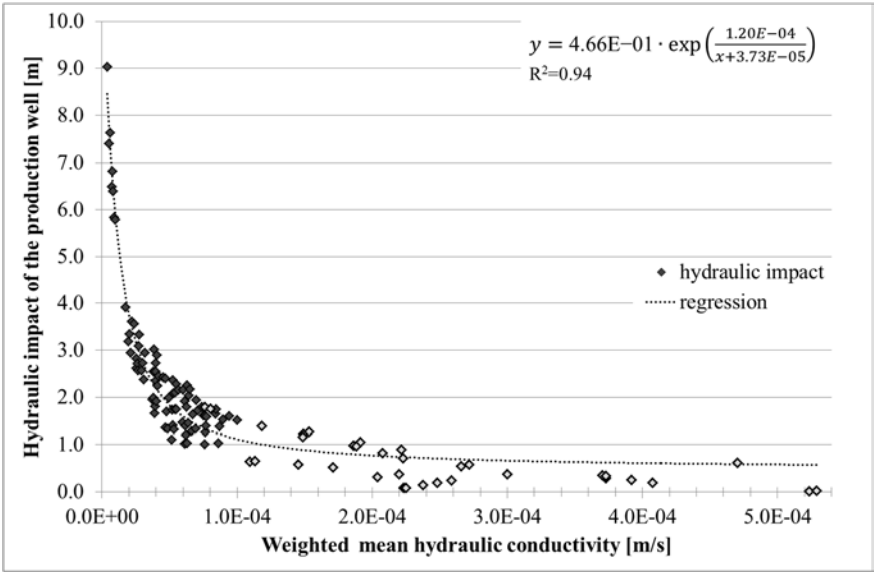

Figure 4: Calculated hydraulic impact of 119 cases in the function of thickness-weighted mean hydraulic conductivity. The white diamonds indicate the second 34 variants.

The thermal impact of the boreholes, as anticipated, did not show such a clear picture. This was partly due to the complexity of the system and partly because the resolution of the grid was somewhat low. This could not be avoided since the larger the resolution the more the numerical errors appear. Beside that there were several cases when the size of the model area was not enough to calculate the magnitude of the thermal affected zone.

The thermal impact appears to different extents in the given layers. The two highlighted layers to which the wells were screened were examined. In the 4^{th} layer the results could be grouped according to the *k* value of this stratum (Figure 5) and the eqn (2) could be used with different parameters to fit the data. Cases when the hydraulic conductivity in the 4^{th} layer was 6.0E-04 are not shown in the chart because these were all beyond the boundaries of the simulation area.

Table 3: Parameters for eqn (2) to calculate the thermal impact in the 4^{th} layer.

	Hydraulic conductivity in layer 4				
	4.0E-06	1.0E-05	6.0E-05	1.0E-04	3.0E-04
a	1.58E+01	1.59E+01	2.33E+01	3.03E+01	6.94E+01
b	3.89E-07	4.26E-06	1.86E-05	2.08E-05	3.06E-05
c	-2.35E-06	4.90 E-06	1.90 E-05	1.93 E-05	5.11E-05
R^2	0.99	0.89	0.87	0.89	0.92

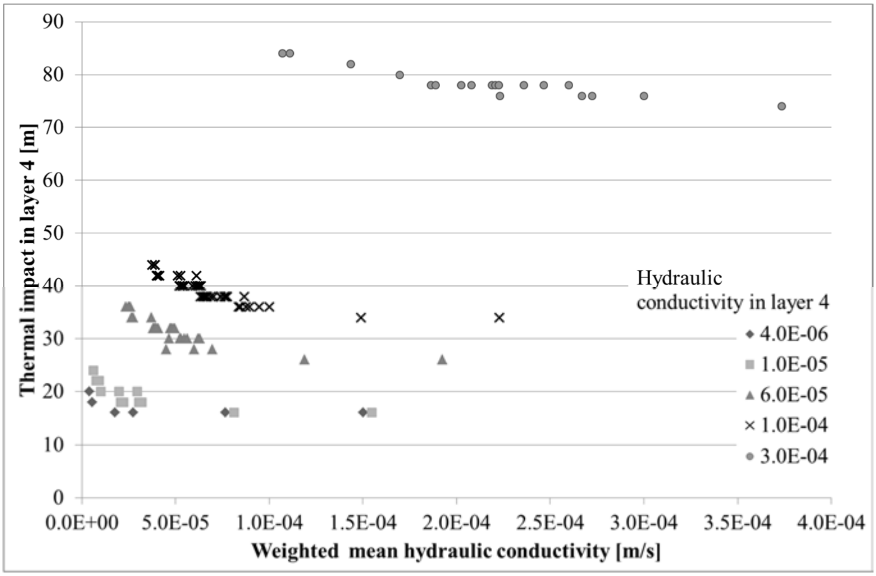

Figure 5: Calculated thermal impact in the 4th layer in function of thickness-weighted mean hydraulic conductivity of 119 cases.

The downstream thermal impact calculated for layer 6 shows similar features (Figure 6) but in this case the categories are not that clear since the injection well also has an impact on this layer due to the vertical movement of the water. Regression analysis was not carried out for these data.

Based on the results it can be stated that if the hydraulic conductivity increases the thermal impact becomes greater. A comparative study on the results showed that if the two key layers have equal hydraulic conductivity (44 cases) the thermal impact in these two layers are either equal (13) or if both neighbouring strata differ, the thermal affected zone in the 4th layer is larger. This is due to the fact that communication between the layers is hindered.

There were only 28 cases when the thermal breakthrough was further in the 6th layer and in all of these scenarios the hydraulic conductivity in the bottom layer outweighed the value in the 4th layer.

4 Conclusions

In this paper the relationship between hydraulic conductivity and thermal impact caused by a single well-doublet was studied in a system with six distinguishable layers. Results showed that a modified exponential decay function can be used to estimate the level of heads in the wells and the hydraulic impact of the production well if the heights and the hydraulic conductivity values of the strata are known. In case of the injection well and the thermal affected zone the information on the average hydraulic conductivity is not enough in itself. In case of the injection well the *k* value of the layer where it is screened is of great importance.

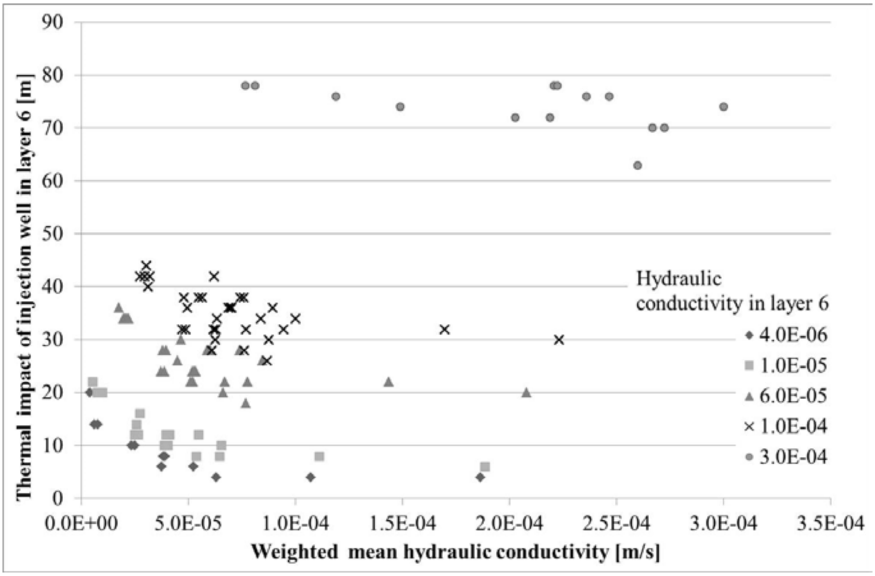

Figure 6: Calculated thermal impact in the 6th layer in the function of thickness-weighted mean hydraulic conductivity of 119 cases.

The extent of the thermal impact has to be determined to a given stratum. In general it can be stated that the largest thermal affected zone is likely to be in that layer to which the injection well was screened but if other layers have larger hydraulic conductivity those have to be taken into consideration as well.

The results also indicate that the change in temperature is dominantly affected by bulk movement as presumed.

Further studies are planned to be carried out with wells screened to multiple layers and to develop a model that depicts the engineering practice of using one single layer with equivalent hydraulic conductivity and the comparison of results with previous multilayer models.

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