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How to assess the thermal plume of groundwater heat pump systems?

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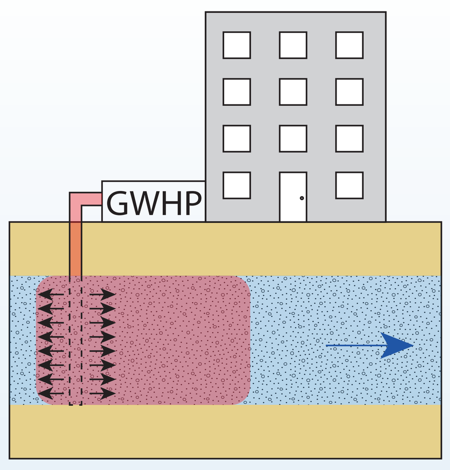
Introduction

The number of groundwater heat pump systems (GWHPS) is growing in many countries and dense installations of urban areas lead to thermal interferences among neighboring wells. The assessment of the thermal plumes caused by GWHPS is a necessary step to manage the geothermal potential beneath cities and to evaluate the feasibility of a project. We focus on following questions:

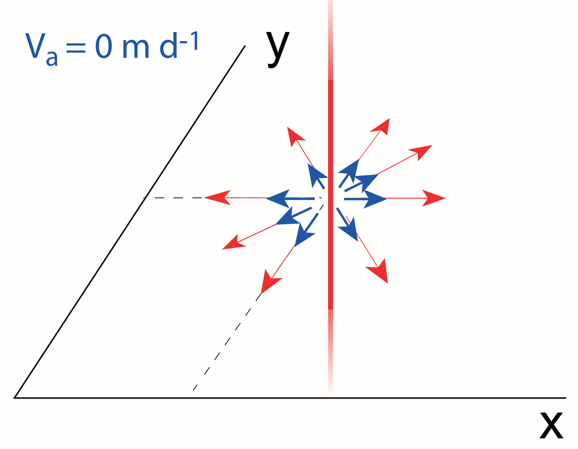
- Should we use analytical solutions easy to implement or time-consuming numerical models?
- How accurate should be the used hydro-geo-thermal parameters?
- How to represent transient thermal impacts of GWHPS?



Suitability of three analytical solutions

The suitability of three analytical solutions – radial (RHM), planar (PAHM), and linear (LAHM) advective models – is assessed under various background groundwater flow velocities. Continuous injections of 120 days ranging from Q_{inj} = 0.3 to 2 l · s^{-1} with ΔT_{inj} = 10 K were calculated.

RHM - Radial heat transport model [1]

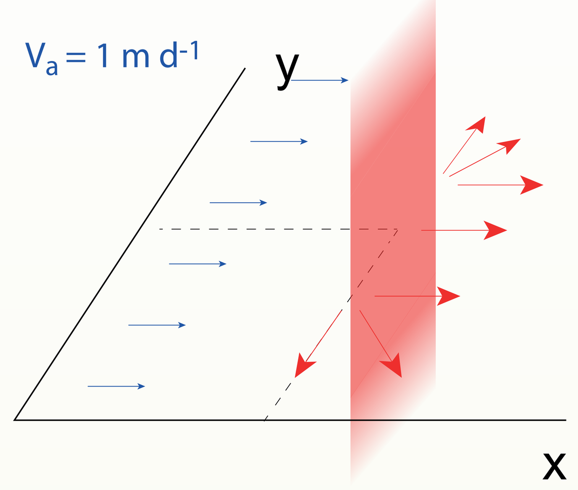


In this analytical model, a continuous line-source and no background groundwater flow are assumed. We calculate the radial heat transport from the injection well. The thermal anomaly is given by:

$$\frac{\Delta T(x,y,t)}{\Delta T_{inj}} = \frac{1}{2}\,\mathrm{erfc}\left\{\frac{r^2-r^{*2}}{2\left[\left(\frac{4}{3}\alpha_L\right)(r^*)^3+\left(\frac{\lambda m}{A_T C m}\right)(r^*)^4\right]^{1/2}}\right\}$$

with $r^* = (2A_T t)^{\frac{1}{2}}$ and $A_T = \left(\frac{nC_w}{C_m}\right)\left(\frac{Q_{inj}}{2\pi nb}\right) = \frac{1}{R}\left(\frac{Q_{inj}}{2\pi nb}\right)$

PAHM - Planar advective heat transport model [2]



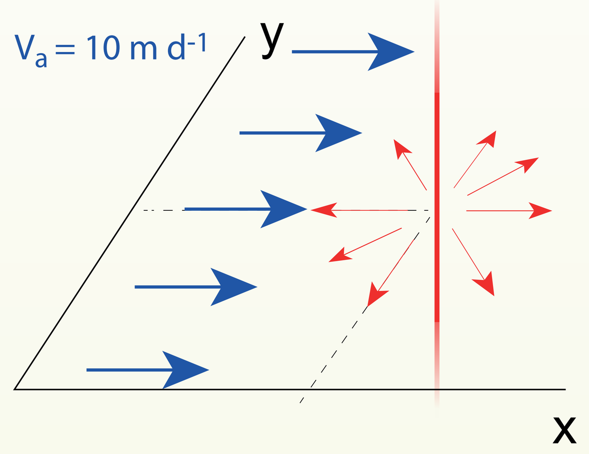
This analytical model describes heat propagation from an injection well with transient conditions, simulated as continuous planar source, considering background flow for a homogeneous confined aquifer. For x > 0, the thermal anomaly is given by:

$$\Delta T(x,y,t) = \left(\frac{\Delta T_0}{4}\right)\mathrm{erfc}\left(\frac{Rx-v_a t}{2\sqrt{D_x Rt}}\right)\left\{\mathrm{erf}\left[\frac{y+\frac{Y}{2}}{2\sqrt{D_y\frac{x}{v_a}}}\right]-\mathrm{erf}\left[\frac{y-\frac{Y}{2}}{2\sqrt{D_y\frac{x}{v_a}}}\right]\right\}$$

with $\Delta T_0 = \frac{F_0}{v_a n C_w Y}$, $F_0 = \frac{q_h}{b}$, $q_h = \Delta T_{inj} C_w Q_{inj}$

$D_{x,y} = \frac{\lambda_m}{nC_w} + \alpha_{L,T} v_a$ $\qquad Y = \frac{Q_{inj}}{b v_a n}$

LAHM - Linear advective heat transport model [3]



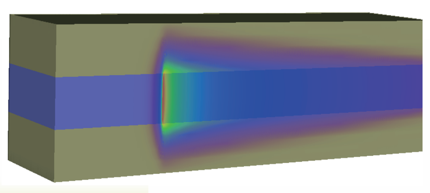
This analytical model describes heat propagation from an injection well with transient conditions, simulated as continuous line-source, considering background flow for a homogeneous confined aquifer. The thermal anomaly is given by:

$$\Delta T(x,y,t) = \frac{Q_{inj}\,\Delta T_{inj}}{4nbv_a\sqrt{\pi\alpha_T}}\exp\left(\frac{x-r'}{2\alpha_L}\right)\frac{1}{\sqrt{r'}}\,\mathrm{erfc}\left(\frac{r'-v_a t/R}{2\sqrt{v_a \alpha_L t/R}}\right)$$

with $r' = \sqrt{x^2+y^2\frac{\alpha_L}{\alpha_T}}$

Comparison with numerical models

The thermal plumes (+ 1 K) calculated by analytical models were compared with two-dimensional and three-dimensional numerical simulations made with FEFLOW [4]:



RHM (Q = 2 l · s^{-1}; v_a = 0 m · d^{-1})

In the radial scenario (no background flow velocity), the comparison between analytical and numerical (2D and 3D) results reveals that the differences of thermal anomalies are only marginal.

The calculation of the relative temperature difference between analytical and 3D numerical models remains below than 30 % inside the plume.

PAHM - (Q = 2 l s^{-1}; v_a = 1 m d^{-1})

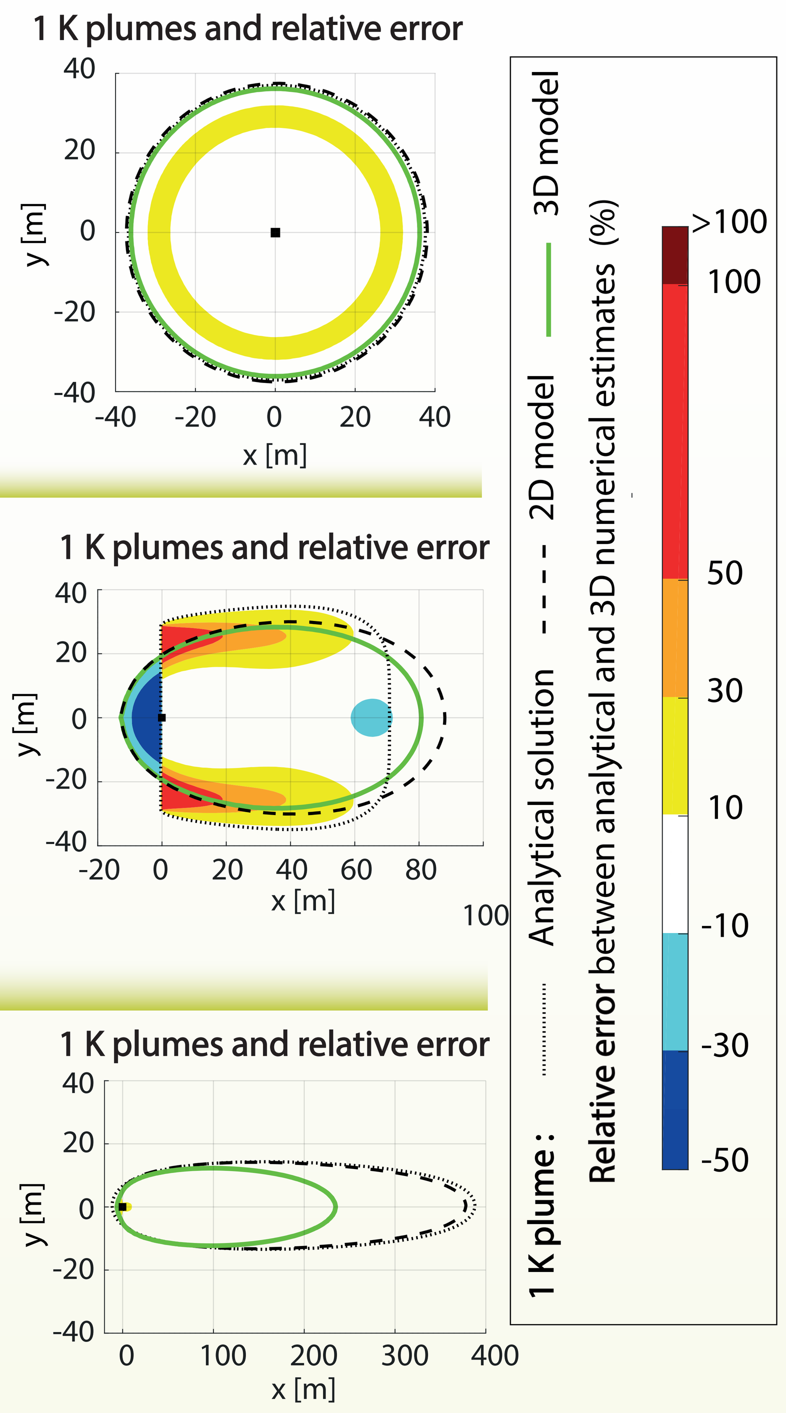
In the first advective scenario (moderate background flow velocity), the comparison between analytical and 3D numerical results demonstrates that heat loss in the top and bottom of the aquifer is higher than in the radial scenario.

However, the 1 K-plume extension estimated by the PAHM remains satisfactory.

LAHM - (Q = 2 l · s^{-1}; v_a = 10 m · d^{-1})

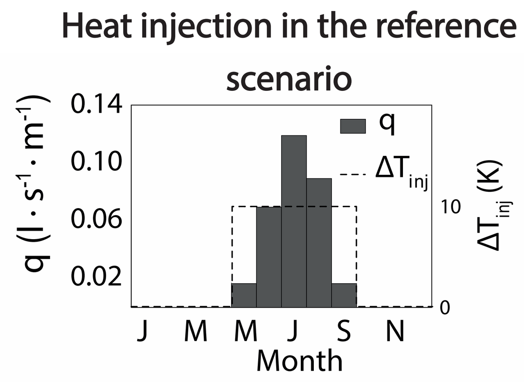
In the second advective scenario (high background flow velocity), the comparison between 1K-plumes extents (analytical and 3D numerical results) reveals the high influence of heat transfer in upper and lower layers.

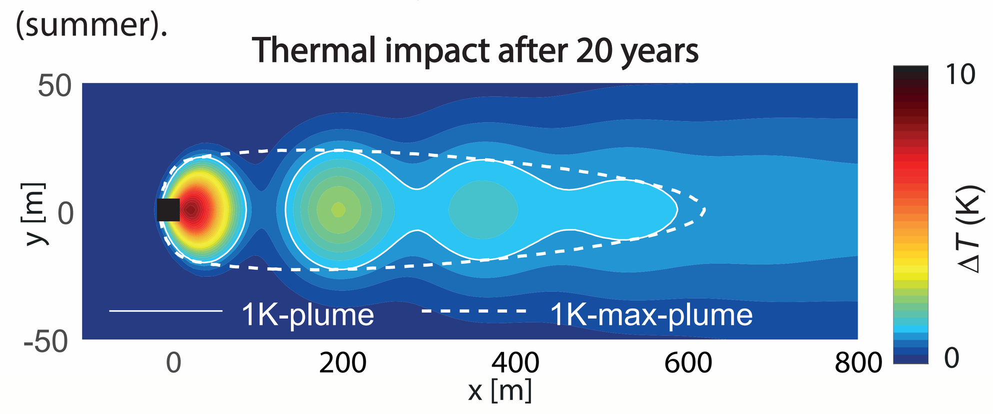
However, the relative error between analytical and 3D-numerical results shows the LAHM ability to estimate the local temperature.



Role played by crucial hydro-thermal parameters

A sensitivity analysis was carried out to scrutinize the influence of (1) background seepage velocity, (2) longitudinal and transverse dispersivity, (3) parameters describing the heat injection and temporal discretization. This sensitivity analysis was performed using 2D (horizontal) numerical models. This study investigates thermal plumes deviation regarding a reference scenario where the open system power ranges from 0 (winter) to 5 kW/m (summer).

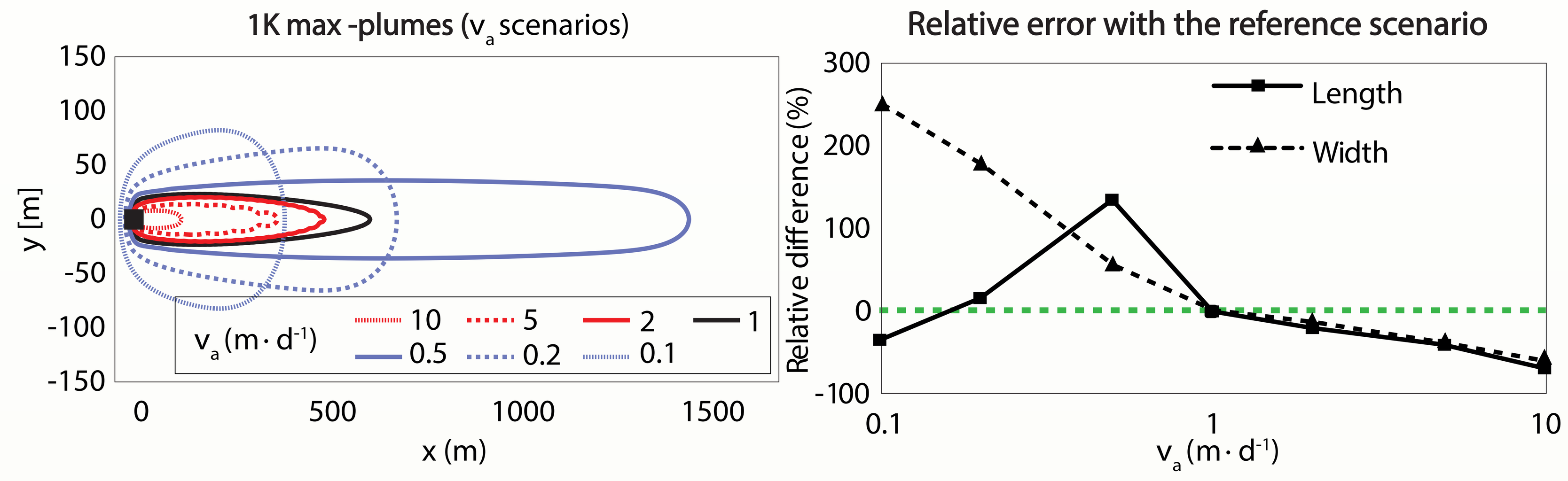




Because the heat injection is transient, seasonal variations of the 1 K plume can be observed. Consequently, the 1K max-plume was considered in the sensitivity analysis. It corresponds to the maximal impact reached over the total simulated period of 20 years.

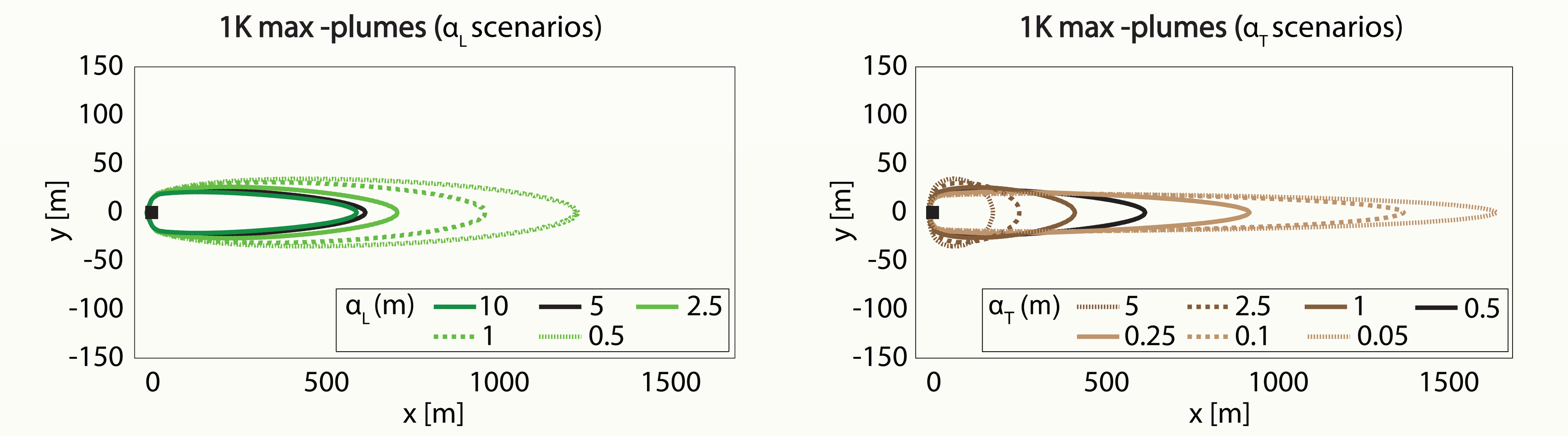
Influence of the seepage velocity

The influence of background seepage velocity is described below. These results put in evidence a reversal point for moderate velocities. This phenomenon can be explained by the transition from a heat transport governed by conduction phenomena to a heat transport governed by advection-dispersion phenomena.



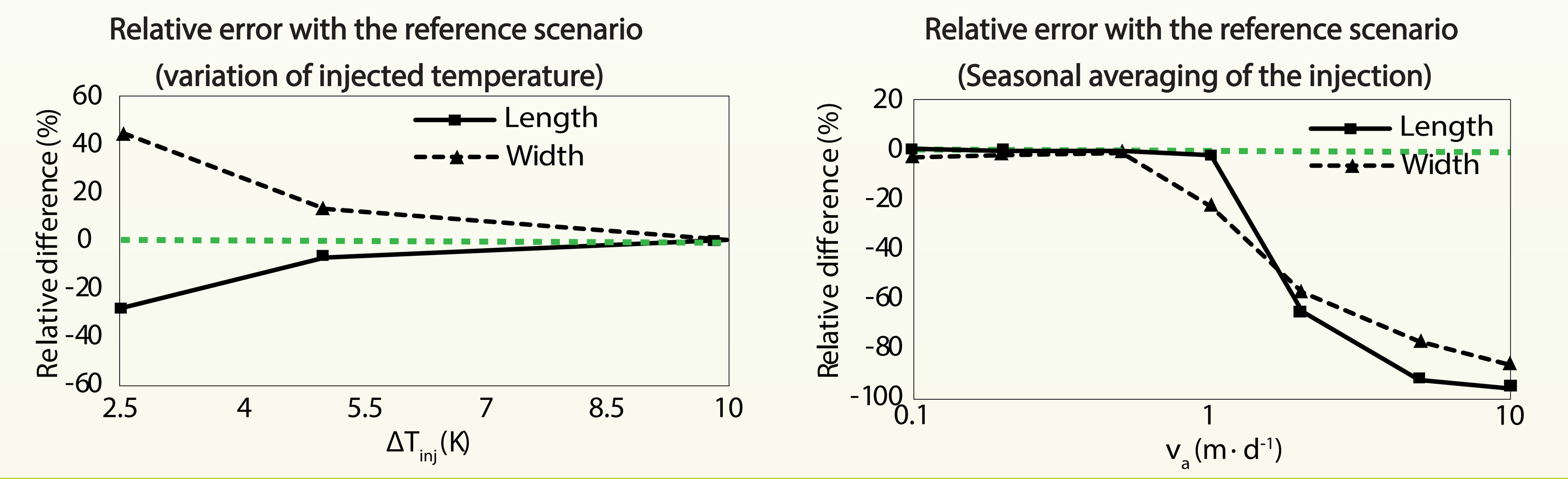
Influence of the dispersivity coefficients

The dispersivity influence has been inspected by separately varying the longitudinal and transverse coefficients. The influence of longitudinal dispersivity on the plume length is strong for low values, and it decreases significantly for values over 2.5 m. In comparison, the transverse dispersivity has a more pronounced influence on the plume length and width.



Influence of the heat injection parameters and seasonal averaging

When the injected temperature is increased, the stronger hydraulic effect of injection generates more radial spreading and thus a greater plume width. The relative difference on the plume extension obtained by considering a seasonal averaging of the variable thermal load shows strong deviations under moderate and high seepage velocities.



Conclusions

This study demonstrates the applicability of three analytical solutions, which are straightforward to use and therefore of interest for the thermal impact assessment of GWHP systems. These analytical solutions are adapted to support integrated spatial planning in case of dense geothermal use in cities. However, the feasibility of a project should be validated by numerical models which offer a better representativity of local thermal anomalies.

Furthermore, the role played by key hydro-thermal parameters was clarified. Particularly, we have demonstrated the strong influence of the seepage velocity and of the dispersivity coefficients on plume extension.

Finally, the relevance of simplified models considering the seasonal average of the heat injection is strongly conditioned by the seepage flow velocity.

References

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Further informations...

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