

Separating Conductive and Advective Heat Transport in Thermal Response Tests

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ABSTRACT

The thermal response test (TRT) is a common method to investigate subsurface heat transport parameters for the sustainable design of ground-source heat pump (GSHP) systems. During the test, the borehole heat exchanger (BHE) is heated up with a defined amount of energy by circulating warm heat carrier fluid. The temperature change between BHE inlet and outlet is recorded, and it reflects the ability of the BHE to transfer heat or cold to the ambient ground. Based on the Kelvin line source theory, the effective thermal conductivity of the ground is derived. In grouted BHEs, which are typical in central Europe, the analytical line source can also be used to estimate the borehole resistance. However, the standard parameter estimation procedure has substantial limitations. A main shortcoming in using the Kelvin line source is that the heat transport in the subsurface is conductive. Thus, the derived effective thermal conductivity is only an apparent parameter, which does not consider any possible advective heat transport in the aquifer. In order to overcome this limitation, we therefore developed a novel parameter estimation procedure, which utilizes the moving line source. Similar to the Kelvin line source, the proposed procedure also uses an efficient analytical method, which is able to separate conductive and advective heat transport processes during the TRT. Due to the competitive character of both components, calibration reveals equally possible parameter combinations. To overcome this critical point an appropriate calibration procedure is necessary to scan all non-unique solutions. The applicability of the moving line source is verified and validated by high-resolution numerical simulation and a range of field and laboratory studies, respectively. The results show that (1) there is a distinct correlation between the derived thermal conductivity and Darcy velocity, (2) for a Péclet (Pe) number < 0.1 , the result is insensitive to the velocity, (3) for moderate velocities, the range of the determined parameter pairs is unequivocal, (4) for Péclet numbers ~ 1 , a wide range of correlated parameter couples are suitable. The novel analytical method thus widens the application range of the TRT to groundwater-influenced conditions beyond a Darcy velocity of 0.1 m day^{-1} .

1. INTRODUCTION

Shallow geothermal energy has a great potential for a sustainable supply of energy and also to save or even reduce greenhouse gas emissions (Bayer et al., 2012; Hähnlein et al., 2013). To better understand and develop shallow geothermal systems, amongst others understanding heat transport processes in the subsurface are essential, thus field investigation methods such as thermal tracer tests (TTT) and thermal response tests (TRT) are commonly applied (Stauffer et al., 2013). The basic principle of the TRT is to thermally stress the subsurface by injecting or extracting heat in or from the subsurface through a borehole heat exchanger (BHE). In general, a TRT device consists of a circulation pump, which controls the flow rate of the heat carrier fluid, temperature sensors connected to a data logger to record the development of the heat carrier fluid temperature, and a heating or cooling device. The thermal response is then typically evaluated to derive the effective thermal conductivity λ_{eff} and the thermal borehole resistance R_b . To obtain these both parameters, the Kelvin line source theory is usually applied. This standard TRT interpretation however exhibits several shortcomings, which are related to the assumptions of the analytical solution (Molina-Giraldo et al., 2011). The BHE is assumed to be an infinite line shaped heat source, which is located in an isotropic, homogenous and infinite medium without advective heat transport. Further, axial heat transport is neglected and a uniform initial temperature distribution of the subsurface is presumed.

The tampering influence of additional advective heat transport on the result of the TRT has been analyzed by field and numerical studies. For instance, Witte et al. (2001) performed a TRT in an aquifer and simultaneously stimulated advective transport in this aquifer by extracting groundwater in a surrounding well (forced gradient experiment). The comparison of the undisturbed and disturbed results of the TRT evaluation exhibited an increase of the resulting effective thermal conductivity by a factor of 1.38. These findings are, amongst others, confirmed by the numerical study of Signorelli et al. (2007). Sanner et al. (2005) proposed a stepwise TRT evaluation as an adequate approach to deduce additional advective heat transport. Wagner and Rohner (2008) applied a depth-depending TRT evaluation to identify, based on elevated λ_{eff} values, indirectly layers with groundwater flow. In contrast to this indirect approach, Raymond et al. (2011) applied a numerical model to TRT field test and they found that the TRT was influenced by groundwater flow velocity smaller than 10^{-5} m s^{-1} . Katsura et al. (2006) evaluated the temperature development of a thermal probe (steel cylinder) based on an analytical equation to determine the groundwater velocity with an error less of 20%.

These previous studies demonstrated in different ways the influence of groundwater flow on the λ_{eff} and R_b values from standard TRT interpretation. The main objective of the current study is to quantify conductive and advective heat transport processes based on the TRT evaluation using an analytical moving line source approach. The presented evaluation approach is related to the procedure of Katsura et al (2006). To be able to consider the impact of grouted BHE on the groundwater flow in close vicinity, a correction factor is introduced. This correction term is derived by detailed comparison of numerically generated TRT data to the results of the applied analytical approach. The novel evaluation procedure is tested to determine the thermal conductivity of the porous media and the Darcy velocity from three different literature based TRT experiments.

2. EVALUATION OF THERMAL RESPONSE TESTS

To be able to derive the thermal parameters of the subsurface by a TRT, an adequate mathematical solution of heat transport at the BHE is needed. This solution is calibrated by varying the free parameters, for instance λ_{eff} and the R_b , to the recorded temperature time series. At the moment, analytical solutions of the heat transport problem are the most common type of mathematical solutions used for this calibration procedure. Among these analytical solutions, the Kelvin line source is the most widely used variant. This solution however assumes the BHE as a constant and infinite line shaped heat source, which is placed in an infinite, isotropic and homogeneous medium. Heat is therefore only transported by conduction. Based on this assumption, the following equation is valid:

$$\Delta T = \frac{q}{4\pi\lambda_{eff}} \int_{\frac{r^2}{4\kappa t}}^{\infty} \frac{e^{-u}}{u} du \approx \frac{q}{4\pi\lambda_{eff}} \left[\ln\left(\frac{4\kappa t}{r^2}\right) - \gamma \right] \quad (1)$$

where q (W m⁻¹) is the heat injection rate per unit length of a borehole, λ_{eff} (W m⁻¹ K⁻¹) the effective thermal conductivity of the subsurface, r (m) the radial distance, t (s) the time, γ (-) Euler's constant, and κ (m² s⁻¹) the thermal diffusivity of the subsurface.

Eq. (1) only considers the heat transport inside the subsurface. Thus, the temperature change from the borehole wall to the heat carrier fluid is not regarded. This temperature transfer can be approximated by the thermal bore resistance:

$$T_f - T_{bw} = q \cdot R_b \quad (2)$$

where T_f (°C) is the temperature of the circulating fluid, T_{bw} (°C) the temperature at the borehole wall, and R_b (m K W⁻¹) the thermal borehole resistance of the subsurface. Combining Eq. (1) and Eq. (2) the fluid temperature of the heat carrier fluid inside the BHE can be assessed by the following expression:

$$T_f \approx \frac{q}{4\pi\lambda_{eff}} \ln(t) + q \left[R_b + \frac{1}{4\pi\lambda_{eff}} \left(\ln\left(\frac{4\kappa t}{r_{bw}^2}\right) - \gamma \right) \right] + T_0 \quad (3)$$

where the r_{bw} (m) is the radius of the BHE. Due to the logarithmic simplification of the exponential integral used in Eq. (3), the parameter estimation can be done by a linear regression.

If there is additional heat transport by advection, the moving line source equation can be applied instead of Eq. (1) (e.g. Molina-Giraldo et al., 2011). This analytical solution considers a BHE as a constant and infinite line shaped heat source, which is placed in an infinite, isotropic and homogeneous medium. The temperature change in the subsurface is calculated as:

$$\Delta T = \frac{q}{4\pi c_{pm} \sqrt{D_l D_t}} \exp\left[\frac{v_{th} x}{2D_l}\right] \int_0^{\frac{v_{th}^2 t}{4D_l}} \exp\left[-\left(\frac{x^2}{D_l} + \frac{y^2}{D_t}\right) \frac{v_{th}^2}{16D_l u} - u\right] \frac{du}{u} \quad (4)$$

where D_l and D_t (m s⁻²) are effective thermal dispersion coefficients in longitudinal and transversal direction, c_{pm} (J m⁻³ K⁻¹) is the volumetric heat capacity of the porous media, v_{th} (m s⁻¹) is the effective heat transport velocity, and u is the integration variable.

Comparable to the Kelvin line source equation, there is also a thermal borehole resistance term needed to consider the temperature transfer between the interface borehole wall to the subsurface and the circulating heat carrier fluid. The resulting analytical formulation for the temperature development during a TRT is as follows:

$$T_f(x, y, t) = \frac{q}{4\pi c_{pm} \sqrt{D_l D_t}} \exp\left[\frac{v_{th} x}{2D_l}\right] \int_0^{\frac{v_{th}^2 t}{4D_l}} \exp\left[-\left(\frac{x^2}{D_l} + \frac{y^2}{D_t}\right) \frac{v_{th}^2}{16D_l u} - u\right] \frac{du}{u} + T_0 + R_b \quad (5)$$

The effective heat transport velocity is defined as:

$$v_{th} = v \frac{c_{pw}}{c_{pm}} \quad (6)$$

where the Darcy velocity is expressed as v (m s⁻¹), and c_{pw} (J m⁻³ K⁻¹) is the volumetric heat capacity of the groundwater. The effective thermal dispersion coefficients D are in longitudinal direction is defined as:

$$D_l = \frac{\lambda_m}{c_{pm}} + \alpha_l v_{th} \quad (7)$$

and in transversal direction as

$$D_t = \frac{\lambda_m}{c_{pm}} + \alpha_t v_{th} \quad (8)$$

where α_l and α_t (m) represent the longitudinal and transversal dispersivities.

3. TRT EVALUATION WITH MOVING LINE SOURCE

First, various TRT temperature datasets are numerically generated to determine if a moving line source (MLS) based TRT evaluation results in a correctly calibrated parameter set. As the MLS equation assumes a homogeneous subsurface around a line shaped heat source, the thermal and hydraulic parameter contrast between the subsurface and the BHE itself is the most obvious source of error for the TRT evaluation. The thermal conductivity difference between the grouting material and the aquifer material is around $1.3 \text{ W m}^{-1} \text{ K}^{-1}$ (Wagner et al., 2013). This difference is rather small. If there is no groundwater flow, the results presented in Fig. 1a, demonstrate that this parameter contrast only results in a temperature difference between the numerical and the analytical solution within the BHE. Hence, the TRT evaluation can be expected to yield the correct parameters of the subsurface.

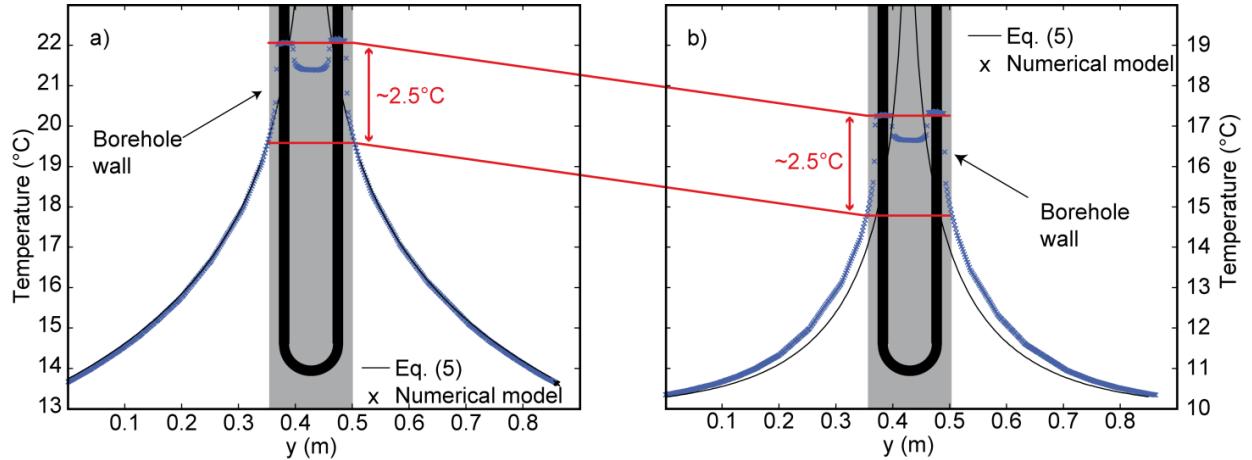


Figure 1: Comparison of the spatial temperature distribution around a BHE perpendicular to the flow direction calculated using Eq. (5) and the numerical model presented in Wagner et al. (2013). a) Temperature distribution for a pure conductive heat transfer around a BHE; b) Temperature distribution for a conductive and advective heat transfer around a BHE (Darcy velocity: $v = 0.5 \text{ m day}^{-1}$). The temperature difference between the heat carrier fluid and the borehole wall is accentuated by red lines (Figure adopted from Wagner et al. (2013)).

If there is additional groundwater flow, also the hydraulic parameter contrast of the aquifer and the BHE has to be considered. In an aquifer with significant groundwater flow, this difference of hydraulic conductivities might be more than several orders of magnitude. This parameter contrast causes a non-uniform groundwater flow field. The results presented in Fig. 1b) show that there is not only a temperature difference between the analytical and the numerical solution within the BHE, but also at the borehole wall. This is a clear indication that a straightforward TRT evaluation will result in incorrect parameters of the subsurface. To analyze this effect in more detail, the difference between the actual Darcy velocity of the numerically obtained TRT dataset and the effective Darcy velocity from Eq. (5), which result in identical temperature time curves, are compared. The results of this comparison are presented in Fig. 2.

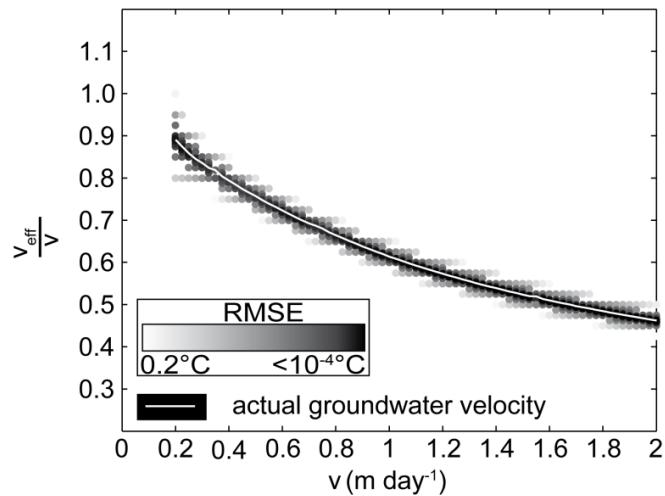


Figure 2: Results of the evaluation of numerically generated TRT temperature time series (influenced by different Darcy velocities) based on the Eq. (5) (after Wagner et al. (2013)).

This comparison in Figure 2 exhibits a non-linear development of the difference between v and v_{eff} between Darcy velocities of 0.2 m day⁻¹ and 2 m day⁻¹. The observed deviation on the groundwater velocity rises with increasing influence of advective heat transport. For a Darcy velocity of 2 m day⁻¹, parameter estimation based on the moving line source equation (Eq. (5)) would result in a Darcy velocity underestimation by 50%, which is an unacceptable deviation and therefore has to be accounted for.

To balance the difference between v and v_{eff} in the TRT evaluation procedure, Wagner et al. (2013) systematically analyzed the relationship between this deviation and the thermal conductivity of the subsurface, the borehole resistance of the BHE, the heat injection/extraction rate per unit length BHE and the regional Darcy velocity in the aquifer. Based on this analysis, Wagner et al. (2013) demonstrated that the v/v_{eff} quotient is nearly independent of R_b and q and that it can be considered as a generally valid correction term C .

$$v \approx v_{eff}^* = \frac{v_{eff}}{C} \quad (9)$$

The dependency of correction term C on $\lambda_{m,eff}$ and v_{eff} is presented in Fig. 3.

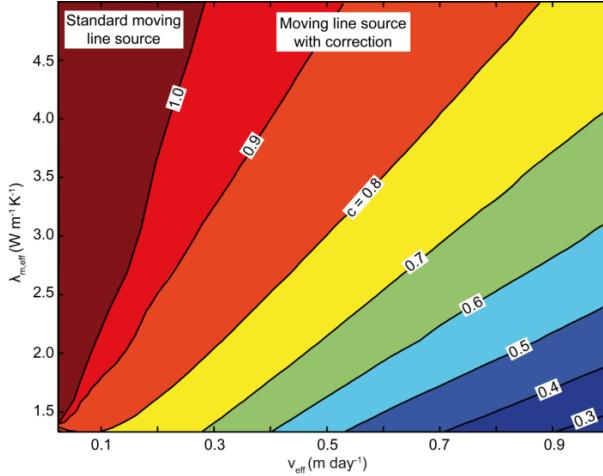


Figure 3: Relationship between the resulting parameters of the TRT evaluation based on Eq. (5) ($\lambda_{m,eff}$ and v_{eff}) and the determined correction term C (after Wagner et al. (2013)).

Utilizing the correction term in the calibration procedure, the following three-steps TRT evaluation approach, which uses the moving line source equation, is proposed to obtain thermal and hydraulic parameters of the subsurface:

- Determination the borehole resistance by a priori knowledge attained from constructing the BHE.
- Estimation of $\lambda_{m,eff}$ and v_{eff} by fitting Eq. (5) to the measured TRT data.
- Correction of v_{eff} by Eq. (9) and the correction factor obtained from Fig. 3.

4. RESULTS AND DISCUSSION

The applicability of the proposed procedure is tested for three different TRT datasets, which are adapted from three different previous studies (Fig. 4). Based on the case-specific thermal and hydraulic properties, numerically generated TRT temperature time series are obtained. The relevant parameters are listed in Table 1. All three datasets are evaluated for the same evaluation period and the results of the newly proposed procedure are compared to the actual hydraulic and thermal parameters (v and λ_m) of the subsurface. The resulting TRT temperature time series are presented in Fig. 4. To be able to compare the advective and conductive portion on the total amount of heat transport, the Péclet number, Pe (-), based on the formulation of Barcenilla et al. (2005), is applied:

$$Pe = \frac{v R_{bw}}{\kappa} \quad (10)$$

Table 1: Thermal conductivities λ_m and λ_g , calculated thermal borehole resistances R_b , and Darcy velocities v from the three case studies for the application of the proposed correction procedure. This table is extracted from Wagner et al. (2012).

	Diersch case	Dornstädter case	Pannike case
Thermal conductivity of the grout, λ_g , (W m ⁻¹ K ⁻¹)	2.3 ^{a)}	0.5 ^{b)}	0.8 ^{b)}
Thermal borehole resistance, R_b , (m K W ⁻¹)	0.05 ^{c)}	0.14 ^{c)}	0.09 ^{c)}
Thermal conductivity of the porous medium, λ_m , (W m ⁻¹ K ⁻¹)	2.5 ^{a)}	1.5 ^{a)}	2.7 ^{a)}
Darcy velocity, v (m day ⁻¹)	0.05 ^{a)}	0.25 ^{a)}	0.86 ^{a)}
Péclet number, Pe (-)	0.05 ^{c)}	0.4 ^{c)}	0.8 ^{c)}

a) values from literature Diersch et al. (2010), Dornstädter et al. (2008) or Pannike et al. (2006), respectively; b) values estimated; c) values calculated based on the reported values and using Eq. (10); d) values calculated based on Eq. (2) and the numerical result.

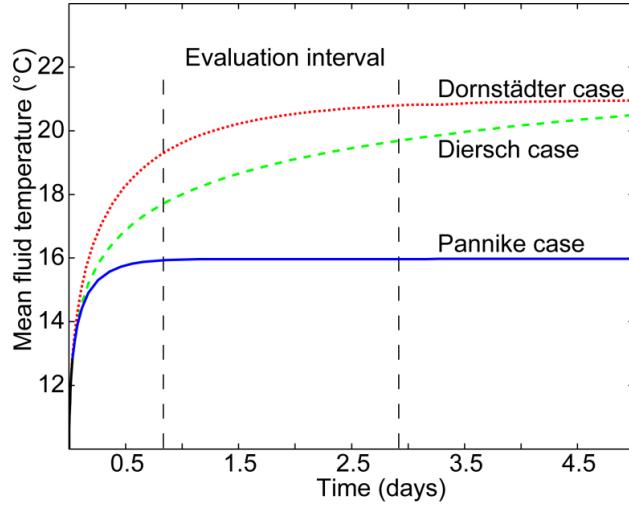


Figure 4: Numerically generated temperature time series of the three evaluated cases (after Wagner et al. (2013)).

Diersch case

Diersch et al. (2010) analyzed a geothermal energy storage installation which is installed in Crailsheim, Germany. The operated BHEs are influenced by an underlying aquifer with a thermal conductivity of $\lambda_m = 2.5 \text{ W m}^{-1}\text{K}^{-1}$ and a Darcy velocity of $v = 0.05 \text{ m day}^{-1}$. The resulting Péclet number of 0.05 indicates that heat transport is dominated by conduction. The results of this moving line source based TRT evaluation are presented in Fig. 5 a). The solution set of suitable v and λ_m combinations shows a distinct negative correlation. This is caused by the competitive character of advective and conductive heat transport. The determined Darcy velocities are very small and the difference between the obtained and actual thermal conductivities is also minor. This indicates that the dominant heat transport process is conduction. A comparison to the effective thermal conductivity, obtained from standard TRT evaluation, shows no significant difference between both values ($\lambda_{m,eff} \approx \lambda_{eff}$).

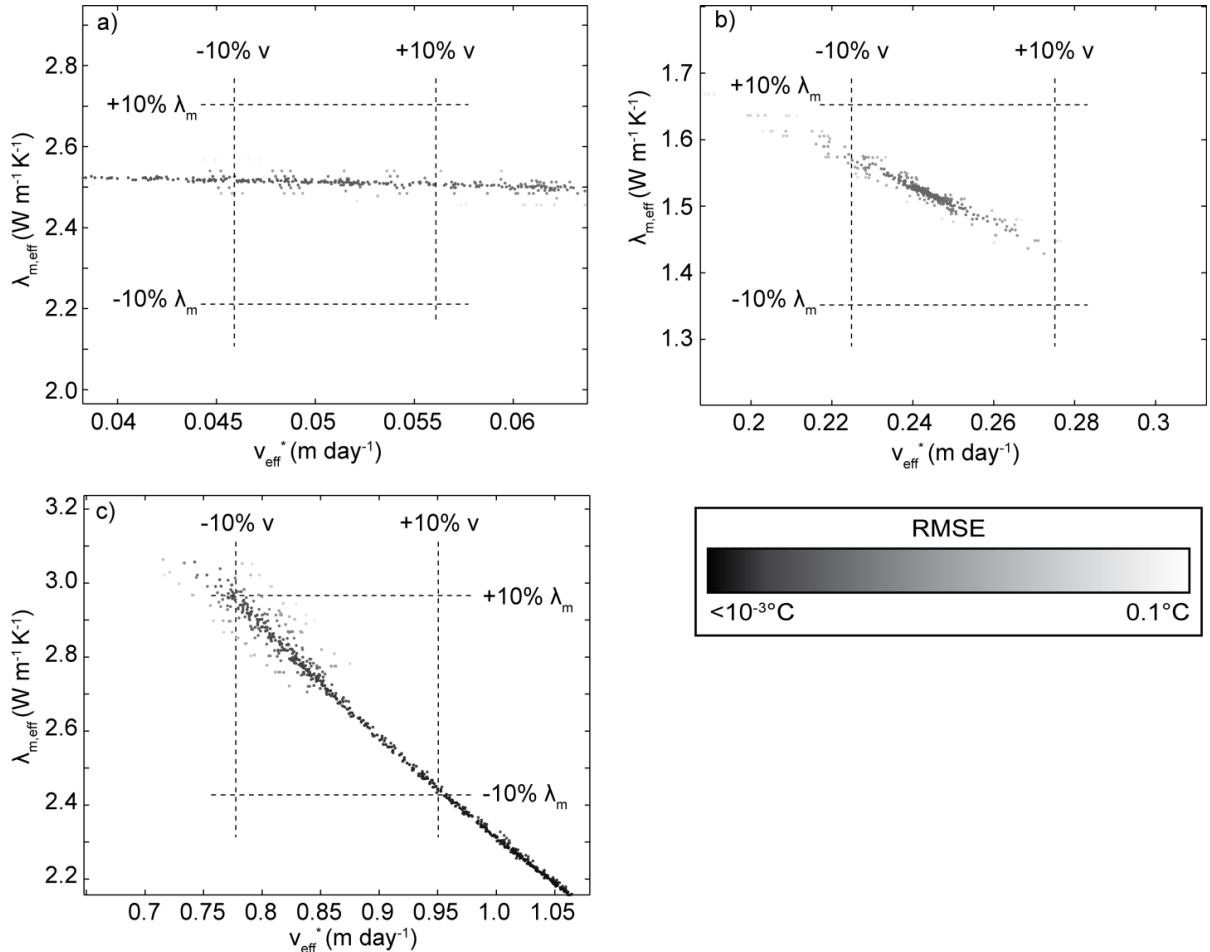


Figure 5: Valid parameter pairs of $\lambda_{m,eff}$ and v_{eff}^* for an RMSE $\leq 0.1 \text{ } ^\circ\text{C}$. Dashed lines delineate a predefined tolerance window of $\pm 10\%$ around the initial values listed in Table 1 (after Wagner et al. (2013)).

Dornstädter case

Dornstädter et al. (2008) evaluated a TRT that is influenced by groundwater flow in a gravel aquifer. The average thermal conductivity of the test site is $1.5 \text{ W m}^{-1}\text{K}^{-1}$ and there is a maximum Darcy velocity of 0.25 m day^{-1} . The determined Pe of this test site is 0.4, which indicates that the advective influence on the total heat transport is considerably higher than for the Diersch case. Suitable best fit parameter pairs, which are presented in Fig. 5 b), exhibit a clear correlation of v and λ_m . Based on the strong advective influence at this test site, the correlation of $\lambda_{m,eff}$ and v_{eff} features a strong negative trend. Nevertheless, the resulting best fitted parameters only slightly exceed the $\pm 10\%$ boundaries of the actual thermal and hydraulic parameters. Thus, the newly developed TRT evaluation turns out to be an appropriate evaluation approach for such advective dominated TRT. This is also demonstrated when comparing the results ($\lambda_{m,eff}$ and v_{eff}) to the heat transport parameter, λ_{eff} , obtained by standard TRT evaluation. The determined λ_{eff} value of $3.5 \text{ W m}^{-1}\text{K}^{-1}$ overestimates the thermal conductivity of the subsurface by a factor of 2.3. Furthermore, standard TRT evaluation provides no information on the degree of groundwater flow.

Pannike case

Pannike et al. (2006) analyzed the thermal anomalies around an advectively influenced BHE by a numerically based study. The properties of the simulated subsurfaces are typical for sediments of northern Germany. The test case extracted for our analysis considers an aquifer with a Darcy velocity of 0.86 m day^{-1} and a thermal conductivity of $2.7 \text{ W m}^{-1}\text{K}^{-1}$. This is the most strongly advectively influenced test case, which is also illustrated by the highest resulting Pe of 0.8. The determined parameter pairs are illustrated in Fig. 5 c). Again, there is a significant negative correlation between $\lambda_{m,eff}$ and v_{eff} , and the resulting parameter set exceeds the $\pm 10\%$ boundary. However, the “true” thermal and hydraulic parameters are within the determined best fitted parameter range. Hence, it is impossible to determine one parameter couple. However, if it is feasible to constrain one of the parameters by *a priori* knowledge, the resulting interval of the other parameter might be reduced. For instance, the thermal conductivity of an aquifer exhibits a small naturally occurring variability compared to the possible fluctuation range of the Darcy velocity. Thus, *a priori* knowledge of the thermal conductivity could be applied to constrain the resulting Darcy velocities. In comparison, the standard TRT evaluation of this test case delivers a λ_{eff} value of $318 \text{ W m}^{-1}\text{K}^{-1}$, which overestimates the λ_m by a factor of 118. Hence, for such a highly advective dominated TRT the proposed approach provides more reasonable values in contrast to the standard TRT evaluation.

5. CONCLUSIONS

This study introduces a novel advection sensitive TRT evaluation approach using the moving line source equation, which is embedded in a three step evaluation procedure. The influence of the parameter contrast between the grouted BHE and the subsurface is considered by a newly developed correction term. First, we demonstrate by detailed comparisons of analytical and numerical results that the discrepancy of the hydraulic conductivity between the aquifer and the BHE causes a non-uniform groundwater velocity field in the vicinity of the BHE, which provokes a considerable difference between both solutions. Hence, for most of the analyzed aquifer settings, the application of the unchanged moving line source based evaluation would result in underestimated groundwater flow velocities. For instance, an aquifer with $v = 1.8 \text{ m day}^{-1}$ and $\lambda_m = 2.2 \text{ W m}^{-1}\text{K}^{-1}$ would underestimate the Darcy velocity by a factor of two using this approach. Then, we developed a correction term to account for this effect and embedded this term in the three-step TRT evaluation procedure. Finally, the newly developed evaluation approach is successfully tested on three different TRT datasets. Comparison of the results obtained by the three step TRT evaluation with the Kelvin line source TRT evaluation demonstrates that there are significant deviations between the actual heat transport parameters of the subsurface (λ_m and v) and λ_{eff} for TRTs influenced by groundwater velocities higher than 0.25 m day^{-1} . The presented Dornstädter case ($v = 0.25 \text{ m day}^{-1}$) results in an overestimation factor of $2.3 = \lambda_{eff} \lambda_m^{-1}$ and the Pannike case ($v = 0.86 \text{ m day}^{-1}$) exhibits a factor of $118 = \lambda_{eff} \lambda_m^{-1}$. In contrast, the three step TRT evaluation yields the $\lambda_{m,eff}$ and v_{eff} values, which are within a $\pm 10\%$ range of the actual values of the subsurface. Thus, we recommend applying the novel three step TRT evaluation, if a site is potentially influenced by significant groundwater flow.

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