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# Analytical simulation of groundwater flow and land surface effects on thermal plumes of borehole heat exchangers

Jaime A. Rivera [a,*], Philipp Blum [b], Peter Bayer [a]

[a] ETH Zürich, Department of Earth Sciences, Sonneggstrasse 5, 8092 Zurich, Switzerland
[b] Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Kaiserstraße 12, 76131 Karlsruhe, Germany

## HIGHLIGHTS

- A new analytical solution for simulating shallow geothermal systems is presented.
- The solution accounts for long-term changes in land use and groundwater flow.
- The approach is verified with a numerical model and validated in a case study.
- Land use changes and horizontal advection can overprint anomalies induced by BHEs.

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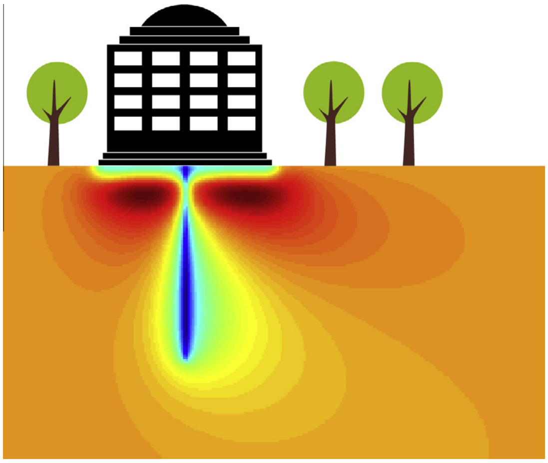
## ABSTRACT



A new analytical model is presented for simulation of ground thermal effects from vertical borehole heat exchangers (BHEs). It represents an extension of the moving line source equation and efficiently describes the coupled transient effects from geothermal energy extraction, subsurface heat conduction, horizontal groundwater flow and spatially variable land use. It is successfully verified by comparison with an equivalent numerical model and validated by application to a field case with detailed long-term temperature monitoring. Non-dimensional sensitivity analysis reveals the coupled influence of advection and conduction for different assumptions of the land surface. Especially accelerated heat flux from asphalt or buildings at the land surface is shown to have a remarkable impact on the thermal conditions in the ground. Together with the flow velocity of the groundwater, it determines the intensity, form and steady-state of the thermal anomaly induced from BHE operation.

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* Corresponding author. Tel.: +41 44 6332594; fax: +41 44 6331108.
*E-mail address:* jaime.rivera@erdw.ethz.ch (J.A. Rivera).

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## Nomenclature

| | |
|---|---|
| $a$ | thermal diffusivity ($\mathrm{m^{-2}\ s}$) |
| $b_1$, $b_2$ | scaling parameters for top boundary temperature functions |
| $c_w$, $c_s$ | volumetric heat capacity of water and of solids ($\mathrm{MJ\ m^{-3}\ K^{-1}}$) |
| $C_p$ | specific heat capacity of the porous medium ($\mathrm{J\ kg^{-1}\ K^{-1}}$) |
| $F_o$ | Fourier number |
| $F_o^w$ | frequency-modified $F_o$ |
| $f$ | spatial distribution function of instantaneous sources or sinks |
| $G$ | Green's function |
| $g$ | spatial distribution function of continuous sources or sinks |
| $H$ | borehole length (m) |
| $J$ | dimensionless form of $j$ |
| $j$ | main integrand function within the MFLS solution |
| $k$ | geothermal gradient ($\mathrm{°C\ m^{-1}}$) |
| $L$ | phase shift of top boundary temperature functions |
| $n$ | normal vector to the plane where heat sources are located |
| $n_e$ | effective porous medium porosity |
| $OH$ | operational hours of a heat pump (h) |
| $Pe$ | Péclet number |
| $q_d$ | Darcy velocity ($\mathrm{m\ s^{-1}}$) |
| $q_L$ | heat flow rate per unit length ($\mathrm{W\ m^{-1}}$) |
| $R$ | dimensionless form of $r$ |
| $r$ | radial distance from the borehole (m) |
| $T$ | temperature in the porous medium (°C) |
| $T_s$ | ground surface temperature (°C) |
| $T_m$ | arbitrary reference temperature (°C) |
| $T_{Pe}$ | temperature calculated for a given $Pe$ (°C) |
| $t$ | time (s) |
| $t_o$ | period of top boundary temperature functions (months or years) |
| $u$ | integration variable |
| $v_t$ | effective thermal velocity ($\mathrm{m\ s^{-1}}$) |
| $\boldsymbol{x}$ | coordinates vector where temperature is evaluated (m) |
| $\boldsymbol{x}'$ | coordinates vector where a heat source is located (m) |
| $x$, $y$, $z$ | single space coordinates where temperature is evaluated (m) |
| $x'$, $y'$, $z'$ | single space coordinates where heat sources are located (m) |
| $\boldsymbol{X}$ | dimensionless form of $\boldsymbol{x}$ |
| $\boldsymbol{X}'$ | dimensionless form of $\boldsymbol{x}'$ |
| $X, Y, Z$ | dimensionless form of $x$, $y$, $z$ |
| $X'$, $Y'$, $Z'$ | dimensionless form of $x'$, $y'$, $z'$ |
| $z^*$ | characteristic length (m) |

*Greek symbols*

| | |
|---|---|
| $\theta$ | dimensionless temperature |
| $\lambda$ | thermal conductivity of porous medium ($\mathrm{W\ m^{-1}\ K^{-1}}$) |
| $\vartheta$ | analytical temperature solution (°C) |
| $\rho$ | density ($\mathrm{kg\ m^{-3}}$) |
| $\tau$ | time at which a heat pulse is released (s) |
| $\varphi$ | top boundary temperature function (°C) |
| $\emptyset$ | dimensionless top boundary temperature function |
| $\Delta\theta$ | dimensionless temperature change |
| $\omega$ | frequency ($\mathrm{month^{-1}}$ or $\mathrm{year^{-1}}$) |

*Subscripts*

| | |
|---|---|
| $a$, $b$ | lower ($a$) and upper ($b$) coordinates of an area with distinctive land use |
| $c$ | continuous heat source |
| lu | land use |
| $o$ | initial conditions |
| $p$ | bulk porous medium property |
| tb | top boundary heat source |

*Abbreviations*

| | |
|---|---|
| BHE | borehole heat exchanger |
| FLS | finite line source |
| GWF | groundwater flow |
| GSHP | ground source heat pump |
| GST | ground surface temperature |
| MFLS | moving finite line source |
| TDP | temperature depth profile |

## 1. Introduction

Borehole heat exchangers (BHE) represent by far the most frequent geothermal applications [1]. In vertical boreholes, plastic tubes are installed, where a heat carrier fluid is circulated. This yields a well-controlled closed system, which exchanges heat with the ground without transfer of mass. The heat carrier fluid commonly feeds an aboveground heat pump that supplies low-temperature heating systems to buildings. Borehole length and number are tailored to a given heating and cooling demand. The boreholes are drilled to depths of tens to hundreds of meters and typically operated for decades [2–5].

BHEs are often applied for heating only, and annual heat exchange with the ground is, therefore, not balanced. Since the usually dominant transport mechanism in the ground, heat conduction, is a slow process, energy deficits are generated, and thermal anomalies develop around the boreholes. Rybach and Eugster [6] estimate the duration of thermal recovery as least as long as the time of operation. This has to be accounted for in design of individual BHE applications, and is a crucial aspect when multiple neighboring installations are operated [7]. Especially in many cities of central and northern Europe, the growing density of BHEs is critically watched [8]. Regulations are sparsely enforced to constrain proliferation, such as minimum distances between adjacent systems and ground temperature thresholds. Recent surveys show that such directives are convenient, however, are also detached from the relevant thermal processes and factors [9,10]. Long-term thermal effects in the vicinity of BHEs are rarely continuously monitored such as at the Elgg site, Switzerland [6], and the field site Bad Wurzach, Germany [11]. Despite decades of experience, there exists no study that provides insight in the temperatures that really evolve from long-term operation of densely arranged BHE applications. Hence, analytical and numerical heat transport models are currently the most important means for predicting future conditions in the ground [12].

There exists a broad range of different modeling techniques and the most common approaches are based on Kelvins line source theory [13–16]. In such (semi-) analytical line source models, the ground temperature field around the borehole is a function of radius and time, calculated based on the heat extraction (or injection) rate. In order to account for the axial effects at the borehole toe, the finite line source model is used and this variant is customarily employed for BHE planning [17,18]. Relying on a model that only addresses conductive heat transport, however, is not always advisable. Horizontal groundwater can additionally carry heat to the boreholes, and this advective transport component is