Impact of Groundwater Flow and Energy Load on Multiple Borehole Heat Exchangers

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Abstract

The effect of array configuration, that is, number, layout, and spacing, on the performance of multiple borehole heat exchangers (BHEs) is generally known under the assumption of fully conductive transport. The effect of groundwater flow on BHE performance is also well established, but most commonly for single BHEs. In multiple-BHE systems the effect of groundwater advection can be more complicated due to the induced thermal interference between the boreholes. To ascertain the influence of groundwater flow and borehole arrangement, this study investigates single- and multi-BHE systems of various configurations. Moreover, the influence of energy load balance is also examined. The results from corresponding cases with and without groundwater flow as well as balanced and unbalanced energy loads are cross-compared. The groundwater flux value, $10^{-7}$ m/s, is chosen based on the findings of previous studies on groundwater flow interaction with BHEs and thermal response tests. It is observed that multi-BHE systems with balanced loads are less sensitive to array configuration attributes and groundwater flow, in the long-term. Conversely, multi-BHE systems with unbalanced loads are influenced by borehole array configuration as well as groundwater flow; these effects become more pronounced with time, unlike when the load is balanced. Groundwater flow has more influence on stabilizing loop temperatures, compared to array characteristics. Although borehole thermal energy storage (BTES) systems have a balanced energy load function, preliminary investigation on their efficiency shows a negative impact by groundwater which is due to their dependency on high temperature gradients between the boreholes and surroundings.

Introduction

Ground source heat energy is becoming increasingly popular as a source of renewable energy for comfort heating and cooling of buildings (Lund et al. 2011). Borehole heat exchangers (BHEs) are one of the most common ways to use ground source heat energy. The heat exchange and thermal performance of BHEs heavily depend on the effective thermal conductivity of the ground. Here, following the definition by Johansen (1977) and Sanner et al. (2005) among others, effective thermal conductivity consists of two components: bulk thermal conductivity of the aquifer (conductive heat transport) and groundwater flow (advective heat transport—converted to conduction equivalent). This definition of effective thermal conductivity is also sometimes referred to as apparent thermal conductivity (e.g., Banks 2012). The point at which advective heat transport becomes important compared to the purely conductive case can be assessed by the thermal Péclet number, a function of bulk thermal properties and groundwater flux (Anderson 2005). The thermal Péclet number describes the ratio of heat transport by advection to conduction. However, using groundwater flux tends to be more precise in the way that it is not dependent on supplementary parameters, such as the characteristic length included in the Péclet number (Chiasson et al. 2000); more so, most of the variability in the Péclet number is due to groundwater flux. Designated values for groundwater flux thresholds can vary slightly based on the ground thermal diffusivity. Nevertheless, as opposed to the arbitrariness of characteristic length in the Péclet number, variations in thermal diffusivity are limited by the thermal properties of geological material in nature. Either way, the Darcy fluxes can be linearly extrapolated between different cases by the $L/\alpha$ relation—where $L$ is the characteristic length and $\alpha$ is the thermal diffusivity. Values for the Darcy flux and the corresponding Péclet number, at which the impact of groundwater advection becomes noticeable has been determined through both real and simulated BHE systems, and thermal response tests (TRTs) (e.g., Dehkordi and Schincariol 2014; Fujii et al. 2005). By enhancing the BHE heat transfer capabilities, groundwater flow can reduce its design depth and installation cost (Wang et al. 558 Vol. 53, No. 4–Groundwater–July-August 2015 (pages 558–571) NGWA.org

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2013). However, as many BHEs are currently designed based on the assumption of negligible groundwater flow, the designed system may not function optimally. Therefore, including groundwater flow in the design procedure can be essential for thermal and economic sustainability of the system. Although using effective (or apparent) thermal conductivity to integrate the effect of groundwater flow in the design is a practical choice under some conditions (i.e., for single BHEs, and when thermal interference between the BHEs is not a concern), it cannot fully address the thermal interference between BHEs in an array, nor it can be used for predicting thermal plume outline—both of which depend on groundwater flow direction.

Thermal sustainability of a single BHE is rather independent of the seasonal energy recharge (Rybach and Eugster 2002). However, in the case of multiple BHEs, borehole spacing is important to limit the thermal interaction between BHEs (Signorelli et al. 2005). This spacing is a function of thermo-geology and system properties. Thermal interaction among BHEs can negatively impact the thermal performance in the short and long term (He 2012). Studying performance of single and multiple BHEs with and without seasonal recharge, Signorelli et al. (2005) found out that for a single BHE, balanced heat load is not necessary while in an infinite field of BHEs it is essential to ensure the long-term sustainability. To ensure production sustainability, they suggest a minimum spacing of 7 to 8 m even in thermally conductivity ground (>3 W/(mK))—under 50 W/m specific heat extraction rate. A study by de Paly et al. (2012) found that by linearly optimizing individual BHE energy loads the maximum subsurface temperature disturbance was reduced by ca. 20%; the improvement in the loop fluid mean temperature was a mere 0.25 °C during a 30-years period. Beck et al. (2013) found that optimizing BHE positions produces nearly the same improvement of the underground temperature change as an optimization of the BHE loads. The combination of both optimization approaches only slightly improves the results by each individual approach. Thus, as Beck et al. (2013) also mention, choosing an optimal BHE arrangement is simpler and more cost effective than regulating the loads, in homogeneous fields without groundwater flow.

Typically, the presumption of negligible groundwater advection and predominantly conductive transport dominates the research literature and governs the design procedure. However, the effect of heat transport by groundwater advection on sustainability of BHEs is receiving increasing attention recently. The transport of heat by groundwater flow can be noticeable in high hydraulic conductivity materials where higher groundwater fluxes increase effective ground thermal conductivity (Chisson et al. 2000). Numerical modeling by Gehlin (2002) shows that temperature in and around a borehole can be significantly affected by groundwater flow. According to Fujii et al. (2005), Péclet numbers higher than 0.1 (associated with a groundwater flux of ca. $10^{-7}$ m/s) enhance the heat extraction rate. Lee and Lam (2009) could estimate the influence of groundwater velocity on TRT at velocities over $2 \times 10^{-7}$ m/s. Advection heat transport by groundwater may alter the temperature distribution near the BHE allowing a steady state condition to be reached more quickly (Diao et al. 2004). Dehkordi and Schincariol (2014) performed sensitivity analyzes on thermal and hydrogeological ground properties and ranked groundwater flux among the top influential factors with regards to the efficiency and impact of BHEs during operation (fluxes above $10^{-7}$ m/s) as well as post-operation recovery of ground temperatures (fluxes above $10^{-8}$ m/s).

In cases of multiple boreholes interacting with groundwater, the interference between BHEs and its consequent impact on whole system thermal performance becomes relevant. Tolooiyan and Hemmingsway (2012) modeled single and 4 × 1 BHEs with unbalanced heating load under pure conduction and mixed conduction-advection (with $1.85 \times 10^{-6}$ m/s groundwater velocity perpendicular to the array axis) regimes; their results show reduction in ground temperature disturbance around the BHE(s) as a result of groundwater flow. Zanchini et al. (2012) modeled one, two, and four staggered lines of infinite BHEs with unbalanced heating load and found that even a modest $6 \times 10^{-8}$ m/s groundwater velocity ($Péclet = 0.02$) reduces the thermal disturbance and accelerates reaching steady state conditions. As an extension to the work by de Paly et al. (2012), Hecht-Méndez et al. (2013) apply their simulation-optimization procedure to a case considering groundwater flow. The effect of optimization appears to become less with increase in groundwater velocity. Choi et al. (2013) modeled nine BHEs in line, L-shaped and square arrays under different groundwater directions. Their results show that the line-type array, followed by the L-type, is noticeably influenced by groundwater direction while the square array is almost unresponsive to it. However, Choi et al. (2013) suggest further research on the role of energy load.

In many buildings the energy demand may not be balanced. Under such circumstances the thermal load of multi-BHE systems can be artificially balanced to avoid excessive temperature changes in the ground or carrier fluid, and the consequent declines in heat pump efficiency factors, or thermal expansion of the ground in extreme cases (Banks 2012). Changes in ground temperatures can also have adverse environmental and ecological impacts (Markle and Schincariol 2007). Note that here we are interested in heat exchange at the underground end of system and not energy demands at the building end. Balance of heat exchange can be significantly different at the demand side in comparison with ground side (e.g., Schibuola et al. 2013). Occasionally, balance in energy loads can be simply a result of symmetry in heating/cooling demands and climate, for example, see the case study in Romania by Polizu and Hanganu-Cucu (2010). The benefits of having a balanced energy load can be so great that users with naturally unbalanced energy demands may choose to artificially balance it through: supplementing the excess need by other sources, harvesting and storing the ambient surplus of energy, or sharing and trading the energy (Banks 2012). However,
generally in borehole thermal energy storage (BTES) systems the annual thermal load is nearly balanced as opposed to ordinary BHE systems (Banks 2012). In such case, the amount of heat that is stored in the ground during the warm season is calculated to be equal to building’s heating needs to guarantee a sustainable operation. While in ordinary (non-BTES) systems the spacing between the boreholes is preferred to be large to minimize thermal interaction between them (often 5 to 10 m), in BTES systems boreholes are more densely located to optimize the storage and extraction of energy (e.g., 3 m at Crailsheim, Germany [Diersch et al. 2010] and 4.5 m at University of Ontario Institute of Technology, Canada [Denicer and Rosen 2007]). Groundwater flow may have a rather significant impact on thermal performance and long-term efficiency of BTES systems (Bauer et al. 2009; Diersch et al. 2011b).

This study uses numerical modeling to evaluate the effect of groundwater flow on thermal interference between boreholes and the overall performance in multi-BHE systems. The configuration of the BHEs (number, layout, and separation) will also be examined in this regard. All the modeling analyzes are done under balanced and unbalanced energy loads to highlight the major distinctions between their effects on long-term thermal sustainability. Moreover, a BTES is also simulated to differentiate between it and an ordinary multi-BHE system with balanced load.

Method and Modeling

The three-dimensional governing equation of heat transport by conduction, Fourier’s law, is written as:

$$\nabla^2 \frac{k}{\rho c} T = \frac{\partial T}{\partial t}$$  \hspace{1cm} (1)

when materials physical properties are temperature dependent. Symbols used in Equation 1 (and the following Equations 2 through 4) are presented in Table 1. In a hydrogeological context, bulk volumetric heat capacity (Equation 2), and bulk thermal conductivity (Equation 3) of the aquifer can be assigned:

$$\rho' c' = n \rho_f c_f + (1-n) \rho_s c_s$$ \hspace{1cm} (2)

$$k' = \epsilon_f k_f + \epsilon_s k_s$$ \hspace{1cm} (3)

For the case of flowing groundwater, the advection component can be added to Equation 1 to keep the energy equilibrium; the simplified equation of heat transport in the subsurface can be written as (after Domenico and Schwartz 1998):

$$\nabla^2 \frac{k'}{\rho c} T - \nabla \frac{\rho_f c_f}{\rho c} T q = \frac{\partial T}{\partial t}$$ \hspace{1cm} (4)

For a more detailed formulation of subsurface heat transport equations see Anderson (2005), Saar (2011), and Diersch et al. (2010) for implementation of governing equations in FEFLOW®.

The modeling is performed in FEFLOW®, a three dimensional (3D) finite element (FE) fully coupled variable density groundwater flow and transport code. FEFLOW® solves the governing flow and heat transport equations for the area surrounding the BHE; a BHE solution is coupled with the rest of the model domain through the temperatures at borehole nodes. The BHE solution, used in this paper, was developed by Diersch et al. (2010, 2011a, 2011b) based on the analytical method by Eskilson and Claesson (1988). Some of the attributes added to the original method are generalized formulations for BHE types, improved relationships for thermal resistances, and direct and non-iterative coupling to 3D finite element discretization of porous matrices. The analytical solution has been validated to be “highly efficient, precise, and robust” and is especially preferred when modeling multiple BHEs due to shorter discretization and simulation times (Diersch et al. 2010).

An assumption of the Eskilson and Claesson (1988) method is that the effect from surface temperature variations is negligible. In accordance with Eskilson (1987), the geothermal gradient is replaced with an average background temperature, that is, 10 °C here. Properties of the modeled single U tube BHE(s) are tabulated in Table 2.

Initially, a single BHE is modeled without groundwater flow and with a 10⁻⁷ m/s flux, under both balanced and unbalanced energy loads, as benchmarks for comparison against multi-BHE grids. The uniform groundwater flux field is created by assigning parallel constant head boundary conditions perpendicular to the no flow boundaries. The balanced and unbalanced energy loads for 1 year are shown in Figure 1 and are repeated over the entire simulation period of 25 years. Equal heat extraction and injection occur in the balanced load, each for 6 months a year; in the unbalanced load heat is extracted...
for 12 months (Figure 1). In both cases the peak specific heat extraction/injection rates are equal, that is, 50 W/m. Four BHE arrays are modeled: 2 BHEs on a 2 × 1 line, 4 BHEs on a 4 × 1 line, 4 BHEs in a 2 × 2 grid, and finally 16 BHEs in a 4 × 4 grid. Each of the arrays is also modeled without and with (10–7 m/s flux) groundwater flow, and under both energy loads. For assessing the induced thermal interference between the BHEs, direction of groundwater flow is chosen such that the thermal interference between the boreholes is maximized (from the work of Choi et al. [2013]). The distance between BHEs in all cases is 7.5 m (based on Signorelli et al.’s [2005] results) except when analyzing borehole separation; in that case the spacing is reduced to 5 m for balanced load and increased to 10 m for unbalanced load. A 4 × 4 BTES with the same borehole and ground properties as Table 1 is also modeled. As previously cited, for the BTES a smaller borehole separation, 2.5 m here, is assigned. The BTES energy load is comprised of a constant inlet temperature of 40 °C during 6 months of heat storage and 5 °C during 6 months heat extraction, with a 10 m3/d fluid discharge rate throughout the year. A summary of the simulation scenarios is given in Table 3.

Mesh convergence studies were carried out paying particular attention to the 4 × 4 grid (unbalanced) and BTES models with groundwater flow. An automatic time step scheme, based on specified solution convergence tolerances, was also employed.

**Results and Discussion**

In the following simulations the loop fluid temperatures are used as an indicator of the system performance conditions. Here, the energy exchange with the ground is following the ground energy loads (Figure 1) while initial ground temperature is set to 10 °C. Loop temperature decrease during heating and increase during cooling (i.e., larger amplitude oscillations from initial ground temperatures considering the same energy load); this indicates reduction in overall system performance—and vice versa for improvement in performance. In this context, oscillation amplitude of loop temperature approaching the steady state is considered as favorable as they stop diverging from the background temperature.

![Figure 1. The balanced and unbalanced energy loads used in the simulations.](image-url)
Effect of Energy Load and BHE Array Configuration

All simulations in this section are with no groundwater flow; the effect of groundwater flow is presented in the next section. To compare the performance of BHEs in different array types (line and square) a constant number of BHEs, that is, four, are modeled in $4 \times 1$ and $2 \times 2$ arrays. Virtually no difference is found in the average loop temperatures for $4 \times 1$ and $2 \times 2$ arrays under a balanced thermal load (Figure 2). In both arrays the temperature oscillations reach a near-steady state quickly. Under the unbalanced thermal load, a decline in average loop fluid temperature with time occurs in both $4 \times 1$ and $2 \times 2$ layouts (Figure 3). This decline is more evident with the $2 \times 2$ layout, suggesting a slightly poorer performance and that a larger distance between BHEs is needed compared to the $4 \times 1$ arrangement. In this case, the performance difference between the two array types becomes obvious after a few years and increases until it reaches a rather near-steady state. This confirms higher sensitivity of thermal performance to borehole array shape under unbalanced thermal loads vs. balanced loads. Although there are correction coefficients for designing borehole separation available, they do not fully account for the balance between heating and cooling loads.

The effect of thermal interference due to the number of boreholes is examined for both line ($2 \times 1$ vs. $4 \times 1$) and square ($2 \times 2$ vs. $4 \times 4$) layouts. For the balanced thermal load, increasing the number of boreholes does not appear to affect loop temperatures. The modeled $2 \times 1$, $4 \times 1$, $2 \times 2$, and $4 \times 4$ arrangements all have virtually the same fluid temperatures over the 25 years (Figure 2); which is also equal to that of a single BHE. This suggests that under adequate borehole separation distance (7.5 m modeled here) long-term sustainability of a multiple BHE system with a balanced thermal load is not sensitive to the number of BHEs. In the case of an unbalanced energy load, the $4 \times 1$ array has fluid temperatures lower than those of $2 \times 1$ array (Figure 3). Compared to a single BHE, the two arrays show approximately $2.2^\circ C$ and $1^\circ C$ drop in minimum fluid temperature, equivalent to 55% and 25%, in the 25th year. The difference in fluid temperatures between the two arrays gradually increases—until they reach near-steady state. Figure 3 shows that a square arrangement is more adversely affected by the increase in thermal interference.
in number of boreholes (4 × 1 vs. 2 × 2). With increase in the number of BHEs the fluid temperatures decrease at a faster rate, that is, the time to reach a near-steady state condition significantly increases and the system may experience a virtually ever-falling performance (2 × 2 vs. 4 × 4). Therefore, as unbalanced systems become larger and have more boreholes the accuracy of design (i.e., BHE length and separation) becomes more crucial in predicting long-term performance and sustainability. It should be noted that FEFLOW® is unable to account for latent heat effects and subsequent phase changes. Thus, temperatures below 0°C only indicate possible ground freezing. In any case the heat exchange is driven by the relative temperature difference between BHE and the ground and not the absolute temperatures.

From the previous results it can be seen that the initial 7.5 m borehole spacing is sufficient to keep the balanced load system thermally sustainable under the examined array configurations. On the other hand, a system with unbalanced load experiences an inevitable deterioration in performance with time, in part due to thermal interference between the BHEs. This decline in efficiency gets amplified by increasing the number of BHEs and changing from line to square layout. One way to reduce the thermal interference between boreholes is increasing the separation between boreholes. Alternatively, heat extraction rates can be modified through increasing the BHE depth which however, will add to the cost. To illustrate the effect of borehole spacing on loop temperatures the distance between boreholes is reduced in the balanced load case and increased in the unbalanced load case, both by 2.5 m and in the 4 × 4 array (Figure 4). In both instances, the impact is observed in loop temperatures as early as the first year. Under the balanced load, although a drop in performance occurs with less distance between BHEs, there is no long-term sustainability concern as it remains stable with time. Under the unbalanced load, increase in BHE spacing improves system performance (i.e., decrease in magnitude of loop temperature oscillations) and shortens stabilization time (decrease in rate of decline from initial ground temperatures). Therefore, in large systems with many boreholes, the distance between the boreholes (or depth) needs to be precisely computed depending on systems energy load function characteristics. Rules of thumb and inaccurate calculations for borehole depth and separation can introduce large accumulative errors.

From the results above, it can be concluded that balancing the energy load substantially lowers the sensitivity of long-term energy efficiency and sustainability to the borehole grid configuration, that is, layout shape, number of boreholes, and distance between the boreholes. In addition, the temperature distribution in the subsurface indicates a substantial difference between the cases with balanced and unbalanced energy loads (Figure 5). After a representative design lifetime of 25 years, the balanced load has led to an almost negligible temperature disturbance (1°C) for the 4 × 4 array, which is constrained mostly to the extent of the borehole array. After the same time period, the unbalanced load causes large changes in the ground temperatures that extend nearly 50 m in diameter at 9°C contour (1°C disturbance). This, in turn, can negatively impact the performance of neighboring installed systems as well as nearby water resources with potential ecological significance.

**Effect of Groundwater Flow**

As previously mentioned, how groundwater flow impacts a BHE has been fairly well studied; the choice of groundwater flux rate in this paper (10⁻⁷ m/s) is based on past studies frequently reporting fluxes in this range (and higher) to have a noticeable influence on loop temperatures (e.g., Dehkordi and Schincariol 2014; Lazzari et al. 2010). According to the results by Choi et al. (2013), a line array is more sensitive to
Figure 5. Ground temperatures under balanced (a) and unbalanced (b) energy loads with no groundwater flow after 25 years. Note the same temperature and length scales. The cross symbols (x) show the location of BHEs.

groundwater flow direction than a square array. The groundwater flow direction simulated here corresponds to the worst case scenarios: parallel to the sides in the square array and along the line array. If groundwater flow is perpendicular to the line array, there will be no advection-induced thermal interference. To evaluate the effect of heating/cooling load in conjunction with groundwater flow, single boreholes with balanced and unbalanced loads are modeled under $10^{-7}$ m/s groundwater flux and compared with the no-flow results. The simulations are then extended to the borehole arrays studied above (i.e., $2 \times 1$, $4 \times 1$, $2 \times 2$, and $4 \times 4$). The single BHE simulations are used again as the benchmark to compare the effect of borehole array configuration on performance in association with groundwater flow.

Loop fluid temperatures in the balanced load systems are insignificantly impacted by groundwater flow (approximately 0.5 °C decrease in loop fluid temperature oscillations and thus small increase in system performance); the impact remains constant during all simulation years (Figure 6 vs. Figure 2). The results also show no dependency on the number or arrangement of boreholes. Therefore, under balanced energy load the effect of groundwater flow on causing thermal interference between the boreholes as well as improving the performance is of less concern. This suggests that the current design approach based on conduction-only heat transport may be acceptable for systems with balanced load. The thermal plume is also insignificantly impacted by the $10^{-7}$ m/s groundwater flow in all balanced load cases considered here. However, while a balanced load is an ideal design situation, achieving a perfect natural balance in system load is not often attained in practice due to variations in climate and building use. Depending on the use, in many buildings part of the heat is generated from electronic equipment and respiring human bodies which lower the heating demand (Banks 2012); in turn, often, this also increases the energy needs for cooling.

Under unbalanced energy load conditions, the decrease in loop fluid temperatures and thus improvement in performance, is initially minor but accelerates with time as the groundwater flow shortens the time to approach a near-steady state (Figure 7 vs. Figure 3). This increasing difference between the pure conduction (0 m/s) and conduction-advection ($10^{-7}$ m/s) conditions becomes more significant from a single BHE to $2 \times 1$, $4 \times 1$, $2 \times 2$, and $4 \times 4$. While earlier results showed that a $4 \times 1$ array clearly performs better than a $2 \times 2$ pattern under unbalanced load in absence of groundwater flow, they perform nearly equally under groundwater flow. As presented in Figure 8, comparing the individual BHE temperatures in $4 \times 1$ and $2 \times 2$ arrays the upgradient borehole in $4 \times 1$ array (borehole a) performs better than the boreholes located upgradient in a $2 \times 2$ formation (boreholes a, b). Moving downgradient, the BHEs in a $4 \times 1$ formation experience more drop in temperature due to interference from upgradient BHEs (Figure 8). In a conduction-only model, the 1st and 4th BHEs (boreholes a, d) in a $4 \times 1$ layout have the best performance while the 2nd and 3rd BHEs (boreholes b, c) perform the worst. This correlates to the well-known principle of superposition, which is familiar to hydrogeologists as in well hydraulics (Fourier’s law analogy to Darcy’s law). This indicates that thermal interference due to groundwater flow may potentially be more relevant in line-type arrays than in square-type arrays—with same number of boreholes. Figure 9 shows the temperature distribution around the BHEs—which is directly linked to the loop temperatures—under the two conditions after 25 years. With groundwater flow the temperature disturbances around the BHEs are lower but a thermal plume is created downgradient. A decision on optimal array type and its orientation, while not complicated itself, requires knowledge of groundwater flow rate and
Figure 6. Average loop fluid temperatures in various array types, under the balanced energy load and $10^{-7}$ m/s groundwater flux.

Figure 7. Average loop fluid temperatures in various array types, under the unbalanced energy load and $10^{-7}$ m/s groundwater flux.

Figure 8. Individual BHE loop temperature in $4 \times 1$ and $2 \times 2$ arrays, under unbalanced energy load and $10^{-7}$ m/s groundwater flux. Boreholes are named $a$, $b$, $c$, $d$ from upgradient to downgradient.
direction, and its seasonal variations. This knowledge requires hydrogeological field investigations which are rarely performed for geothermal installations. Groundwater flow only slightly alters the thermal plume when the load is balanced in contrast to the unbalanced load where groundwater flow causes considerable change in ground temperatures.

In the 4 × 4 array and under unbalanced energy load, a large temperature difference (more than 4 °C) is observed between the upgradient and downgradient BHEs as a result of advection-driven thermal interference (Figure 10). Although in the first few years no significant improvement is noticed in loop temperatures due to enhanced heat transport by groundwater flow; it becomes noticeable as the temperatures approach steady state (4 × 4 in Figure 7 vs. Figure 3). In addition, ranking of boreholes by their temperature completely changes compared to the no-groundwater flow model; the downgradient BHEs generally perform worse. The time to reach near-steady state is about 5 years for the upgradient BHEs but becomes nearly double for the downgradient BHEs—in the 4 × 4 array. In large BHE arrays where more extreme loop and ground temperatures are produced, groundwater flow can substantially prevent the manifestation of extreme temperatures and improve the overall thermal performance. However, generally in arrays with more boreholes thermal interference becomes more relevant.

The thermal plume developed under unbalanced energy load is substantially more sensitive to groundwater flow than it is with balanced load (Figure 10 vs. Figure 5). The advective transport of the thermal plume by groundwater in large systems can have downstream thermal and environmental implications, the significance of which increases with time. Although groundwater flow disperse the plume and reduces temperature differentials downgradient, the thermal plume will be more spread and subject to uncertainty depending on groundwater flow rate and direction (Casasso and Sethi 2014; Choi et al. 2013; Lo Russo et al. 2012). Therefore, hydrogeological data collected over sufficient period of time to capture changes in hydraulic gradients, is important for large multi-borehole systems to ensure optimal system performance, to prevent interaction with nearby BHE systems, and to protect groundwater and surface water resources, as well as related ecological features. A number of scenarios could be modeled to increase the confidence in the design and predicted impacts.

Groundwater advection and the spacing between the BHEs are two factors that can affect the thermal interaction among the boreholes. The joint effect of these aspects is analyzed by varying the parameters individually and simultaneously. Under the balanced energy load performance is slightly affected by changing the distance or introducing groundwater flow alone (Figure 11). Simultaneously increasing borehole separation and introducing groundwater flow causes more impact on the loop temperatures. The amount of influence depends on the amount of variation in BHE distance and groundwater flux. For example, here a 2.5 m increase in the distance has more impact than introduction of 10⁻⁷ m/s groundwater flow. A larger increase in groundwater flow will have a larger impact on the temperatures ranges. When the energy load is unbalanced both borehole separation and groundwater flow become increasingly important for system efficiency (Figure 12). However, groundwater flow is more effective in shortening the time to reach near-steady state. In the scenarios shown in Figure 12, the array with 10 m borehole separation and no advection initially has better performance than the system with 7.5 m separation and a subtle 10⁻⁷ m/s groundwater flux. Within the modeled timespan, the system in a conduction-only environment (10 m separation) undergoes a continuous fall in performance while the other system (7.5 m separation and

Figure 9. Ground temperatures around 4 × 1 boreholes in the 25th heating season under unbalanced load with no groundwater (a) and 10⁻⁷ m/s flux (b). Flow is in the direction of the arrow. The cross symbols (x) show the location of BHEs.
advection) approaches steady state conditions. At the end of the design timespan, the case with smaller BHE separation has better performance due to groundwater flow. The time and significance for occurrence of this phenomenon depend on the BHE spacing and groundwater flow.

**BTES Systems**

BTES systems work on the same basis as ordinary BHE systems with a balanced energy load. However, BTES systems are usually meant to be used only for heating (or cooling) in one season, while during the other season the energy is continuously stored in the ground to serve the heating (or cooling) purpose in the upcoming period. This makes the annual energy exchange with the subsurface (nearly) balanced despite the energy demand being heating (or cooling) dominated. To illustrate the potential impact groundwater flow can have on a BTES system, a comparison is made with the ordinary BHE system with a balanced load.

With no groundwater flow, the essentially balanced BTES energy load produces 33.8°C loop outlet temperature at the end of the 1st storage season which increases to 34.7°C in the 25th year (Figure 13). Thus, the temperature difference between inlet (40°C) and outlet decreases from 6.2°C to 5.3°C which entails that the amount of stored energy somewhat decreases with time. At the end of 1st and 25th energy extraction seasons the temperature gains (from 5°C inlet) are, respectively, 2.5°C and 3.3°C, showing an increase in heating performance. In the presence of a 10⁻⁷ m/s groundwater flow, outlet temperatures are slightly lower during storage, 33.4°C and 33.9°C creating 6.6°C and 6.1°C temperature difference between inlet and outlet (Figure 13). Therefore, in this case approximately 10% more heat is being put into the ground compared to the no-flow conditions. However, this does not lead to higher temperature gains during extraction (i.e., 2.5°C and 2.8°C for years 1 and 25). As the loop temperatures indicate, with the addition of groundwater flow, the modeled BTES performs progressively less efficiently during its entire lifetime. Groundwater flow also deteriorates the actual energy storage capabilities of BTESs. In this instance, overlooking the groundwater flow in system design causes a 16% overestimation in heat production rate at the end of the 25th heating season. The increase in energy input to the subsurface and the subsequent decrease in energy extraction caused by groundwater flow, lower the energy efficiency of the system. With more heat being introduced into the underground, the potential for thermal and environmental impacts also increases. A virtually infinite amount of energy exists in the subsurface; however, to efficiently extract it high temperature gradients between the BHE and ground are needed. By storing heat and increasing temperatures locally, BTES systems facilitate higher thermal gradients and effective (re)extraction of energy; groundwater advection only hinders this process by displacing some of the heat energy away from the BTES boreholes.

Comparison of thermal plumes under pure conduction and mixed advection-conduction shows that groundwater flow spreads the thermal plume well beyond the extent of the BTES in the flow direction (Figure 14). Because large temperature gradients are present in BTES systems, the magnitude of the downgradient temperature disturbances is rather high despite the added effect of dispersion. By the end of the heating season the entire high temperature zone (stored heat) is transported downgradient, away from the BHEs, becoming wasted and unusable by the system. Note the assigned 10⁻⁷ m/s flux is at the lowermost reported range for having noticeable impact on TRTs and non-BTES systems. Further sensitivity analysis exclusively for BTES systems may be necessary to find groundwater flow thresholds with regards to storage and extraction temperature gradients.
Conclusions

This study used numerical modeling of hypothetical cases to analyze the influence of groundwater flow (0 m/s vs. 10^{-7} m/s) on BHEs with balanced and unbalanced thermal loads, as well as on a BTES system. The average BHE-field loop fluid temperature, thermal interference between individual BHEs in the field, and the disturbance to subsurface temperatures due to the produced thermal plume are examined.

When the heating and cooling loads are balanced, sensitivity of the produced temperatures to the array shape and number of boreholes are minor. The loop and disturbed ground temperatures are still affected by the distance between the boreholes; this effect remains constant and does not accumulate with time. Therefore, methods for balancing the energy load, considering economic and mechanical feasibility, are a useful area of investigation given their potential effect on enhancing the thermal and environmental sustainability of BHE systems. Moreover, the presence of groundwater flow has less impact on improving the performance of balanced load systems. A complete balancing is necessary in areas with negligible groundwater flow; in presence of groundwater flow a partial energy balance is expected to improve the sustainability.

When the energy load is unbalanced, the design sustainability (i.e., the loop temperatures and level of disturbance to ground temperatures) strongly depends on the number of boreholes in the grid and their positions (i.e., array form and borehole spacing) in the absence of groundwater flow. The system efficiency declines and its impact continuously deteriorate with time until reaching a near-steady state. Therefore, carefully choosing the design lifetime is an essential aspect of system long-term sustainability. If the system has reached its near-steady state within the design period, it may be serviceable beyond the design period, for example, retrofitting.
Figure 13. Comparison of inlet and average outlet temperatures in the 4 × 4 BTES, under 0 and \(10^{-7}\) m/s groundwater fluxes.

Figure 14. Ground temperatures in surroundings of the BTES peaking in the 25th cycle of heat storage (a, b) and dissipating after the extraction in the end of the 25th year (c, d) with no groundwater (a, c) and \(10^{-7}\) m/s flux (b, d). Flow is in the direction of the arrow. The cross symbols (×) show location of the BHEs.
Otherwise, a reduction in efficiency is expected; future installations require new design and possibly relocation. When the energy load is unbalanced, groundwater progressively enhances the thermal efficiency by transferring heat away from the BHEs and reducing generated subsurface temperature anomalies. Groundwater becomes a more important design consideration as the loop temperatures become greater in magnitude, for example, by switching from line to square array and increasing the number of BHEs. Our results show that advection-driven thermal interference between the BHEs in a line arrangement—when groundwater flow is parallel to its axis—can be higher than a square array with the same number of BHEs. This thermal interference to some extent offsets the enhancement in performance due to groundwater flow. However, the thermal interference in line array is sensitive to the direction of flow. Therefore, when the direction of groundwater flow is unknown, or varies temporally and spatially in different encountered formations, the design can be more confidently done in square array.

Knowledge about the effect of groundwater flow on performance of BHEs has evolved considerably, especially in the recent years; it has illustrated the necessity of including groundwater flow in the design process in certain cases. Borehole depth and spacing are two of the major BHE system design factors. The results given here prove that, when assessing the performance of BHEs, the difference between designs with and without groundwater flow becomes larger with time; and that groundwater flow can be more important than borehole separation in the long-term. Accordingly, the optimal design can be achieved integrating groundwater flow. A system, designed not considering groundwater flow, will become more overdesigned and economically unsustainable under longer design periods.

Conversely in BTES systems, groundwater flow can have undesired impacts. The example modeled here shows that a modest groundwater flux of $10^{-7}$ m/s reduces the heat delivery rate by ca. 15%. This is despite more heat being injected into the subsurface (10%). The introduction of more heat and the advection-dispersion transport processes produce greater impact zone but slightly reduced temperature differentials. As a BTES system and non-BTES system with balanced heating-cooling loads, react differently to interaction with groundwater, further study is required to provide guidance in order to draw a line between the two system types in interaction with groundwater. In addition, most of the groundwater flux values, reported as threshold for noticeable impact on loop temperatures, are for non-BTES systems. Thus, further research on the effect of groundwater flow on performance of BTES systems is recommended.

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