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Hydrogeological and Thermal Sustainability of Geothermal Borehole Heat Exchangers

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Geology

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HYDROGEOLOGICAL AND THERMAL SUSTAINABILITY OF GEOTHERMAL BOREHOLE HEAT EXCHANGERS

(Thesis format: Integrated Article)

by

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Graduate Program in Geology

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

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Abstract

Assessment of the current approach taken by guidelines and design methods of vertical closed loop heat exchangers shows that often groundwater flow is either disregarded or is not methodically incorporated. The state of scientific research in this arena reveals that overlooking the groundwater flow in the design procedure may not always be a correct assumption. The significance of advective heat transport compared to conduction is defined by the groundwater flux or Darcy velocity which heavily depends on the hydraulic conductivity of the ground, followed by the hydraulic gradient which has a relatively limited range. A sensitivity analysis on ground and borehole properties ranks groundwater flux together with the thermal conductivity of the ground and the temperature gradient between the antifreeze and the ground (i.e. inlet and background temperatures) as the key factors defining the heat exchange efficiency. The study confirms that the effect of groundwater advection on an operational borehole heat exchanger (BHE) becomes notable at fluxes $\geq 10^{-7}$ m/s; fluxes $\geq 10^{-8}$ m/s accelerate the returning of ground temperatures to the initial background temperature (i.e. thermal recovery) when the BHE is not operational. Examining the groundwater flow impact on multiple BHEs shows that as increasing the number of boreholes causes larger temperature disturbances, the effect of advective transport becomes more substantial. The thermal interference between BHEs induced by groundwater flow in line arrays can be of higher relevance than square arrays, depending on the flow direction. Although the BHE spacing is a major design parameter, in the long-term groundwater flow may be more critical to improving the thermal performance of the system as it considerably shortens the time to reach steady state. The effect of hydrogeological inhomogeneities, i.e. fractures, depends on their dip angle. Modeling of vertical features up to 10 m away from a BHE with aperture ≥1 mm, which can be recognized through geological investigation techniques but not thermal response testing (TRT), shows long-term impacts. Depending on the openness and distance from the borehole, one major fracture has the most influence on the BHE. For horizontal features, fracture frequency is the key parameter to consider.

Keywords

Borehole heat exchanger, Borehole spacing, Borehole thermal energy storage, Design, Earth energy, Efficiency, Energy load, Fracture, Geoexchange, Geothermal, Groundwater flow, Guidelines, Heat pump, Heat transport, Heterogeneity, Inhomogeneity, Legislations, Performance, Regulations, Temperature, Thermal conductivity, Thermal interference, Thermal recovery, Vertical closed loop

Co-Authorship Statement

Hereby, I solemnly proclaim that as the lead author of all the publications included in this thesis, I have commenced and performed the research from the literature review, setting up and running the models, to analysing and interpreting the results, writing the original manuscripts and following correspondences.

I would like to acknowledge the contribution from my co-authors in the articles forming this thesis: Dr. Robert Schincariol and Prof. Bo Olofsson.

Dr. Robert Schincariol provided guidance on conduction of the research, as well as on the analysis, interpretation and presentation of the results. He reviewed all the articles and this thesis, and provided numerous invaluable recommendations and meticulous remarks.

Prof. Bo Olofsson acted as an external advisor at the Royal Institute of Technology (KTH), Stockholm, Sweden. He contributed by offering his expertise input, reviewing the articles and providing comments.

Dedication

To the most wonderful person in my life, my son, Kian.

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Chapter 1

1 Synopsis

1.1 Rationale of study

Renewable energies are becoming increasingly popular due to their near inexhaustibility, generally lower emissions and lifetime costs, higher reliability and more stable prices, compared to fossil fuels such as oil. Geothermal, defined as the thermal energy stored in the Earth, is a renewable source of energy. Conventional geothermal technology often deals with temperatures near the boiling point of water which limits its applicability to specific locations. At the lowest end of the geothermal energy spectrum, in terms of temperature, is ground source heat which utilizes energy from “normal” ground temperatures predominant across the earth. Low temperature geothermal, or ground source energy, is commonly used for space heating and cooling in buildings which makes it economically attractive to domestic and commercial consumers. Despite being “sustainable” by nature as a renewable energy, “unsustainable” use of ground source energy can potentially cause some environmental problems, and diminish performance efficiency. A prevalent method of extracting ground source heat energy is through borehole heat exchangers (BHEs) which interact with the subsurface saturated zone, and whose performance involves both the mechanical system properties and hydrogeological aspects.

The transport of heat in the solid phase is governed by Fourier’s law which relates the specific heat flux rate to the temperature gradient and thermal conductivity, analogous to Darcy’ law. In saturated porous media, heat transport occurs through: 1) conduction in the solid phase, 2) conduction in the liquid phase, and if groundwater is flowing, 3) advection in the liquid phase and 4) hydrodynamic dispersion in the liquid phase. From the conservation of mass and energy, heat transport by the soli-fluid matrix is formulated as:

$$\frac{\partial T}{\partial t} + \frac{\rho_w c_w}{\rho c} \nabla T q - \left(\frac{\lambda}{\rho c} + \alpha q \right) \nabla^2 T = 0 \tag{1.1}$$

where T is temperature, t is time, λ is the solid-water matrix thermal conductivity, α is dispersivity, q is specific groundwater discharge, ρ is density and c is volumetric heat capacity (w denotes the water phase). At sufficiently high groundwater flow rates, the heat transport by advection may become more significant than by conduction, and is no longer negligible. This is often enumerated by the dimensionless thermal Péclet number (Pe) as a rough indicator:

$$Pe = \frac{\rho_w c_w q L}{\lambda} \tag{1.2}$$

where L is a characteristic length of the model.

1.1.1 Research objectives

In brief, this thesis aims to put borehole heat exchangers in a hydrogeological context, specifically in regard to groundwater flow, and to evaluate their environmental and thermal sustainability in that perspective. Thereupon, quantifying the effect of groundwater flow on BHEs loop temperatures and studying the behaviour of conforming thermal plumes are the main supplementary objectives. Concerns with thermal sustainability can emerge from both internal and external factors. Within a multiple borehole geothermal system, thermal interaction between BHEs, which may or may not involve groundwater flow, can influence thermal sustainability. The inter-borehole thermal interference may depend on the thermal load of the system, i.e. heating or cooling only vs. heating and cooling vs. heat storage and reuse. Thus, this work will also asses at how the long-term sustainability of multi-borehole geothermal systems is influenced by its energy load and groundwater flow; and how effective are the design aspects, e.g. borehole spacing. The final goal of this work is to differentiate between homogenous and heterogeneous geologies (i.e. fractured rock), thereby extending the main objective of this study to non-homogenous conditions, and to determine what fracture properties are of principal significance. Each of the four papers that comprise this thesis is intended to answer one of the above questions and is based on the findings from the previous paper and other referenced studies. Below is a short summary relating all the papers to objectives of the thesis. In the next section "*1.2 Thesis organization*", more details on the results from each paper are presented as a guide to prepare the reader in going through this thesis.

In most countries where the geothermal industry is still undeveloped and immature, unsuccessful application of BHEs can hurt the reputation of the technology and its development. Alternatively, areas where the geothermal business is advanced have higher failure risks due to potential negative interactions between a larger number of installations. This study begins with an assessment of the current status of the scholarly literature, design practices, and the state of the industry and regulatory framework. The review reveals that groundwater flow is a potential factor influencing the performance efficiency of BHEs as well as their adverse impacts on the environment or adjacent BHEs. Groundwater flow is routinely not incorporated in the design process, and is seldom and only vaguely covered in the regulatory environment. This is despite the fact that tools for integration of groundwater flow in modeling already exist (e.g. Diao et al. 2004; Diersch et al 2011a and 2011b; Molina-Giraldo et al. 2011). Thus, the approach taken here is to first use these tools to analyse the effect of groundwater flux along with other hydrogeological and thermal factors on a single BHE. This is an original approach to investigating these factors in the sense that they are studied within the same framework; therefore, they can be properly compared against each other. The results rank groundwater flux among the top influential parameters. Knowing that groundwater flow is of high importance, the analysis is extended to multiple-borehole systems with various configurations. In multi-BHE systems, energy load balance (or lack thereof), which is unimportant in single BHEs, becomes relevant (Rybach and Eugster 2002; Signorelli et al. 2005; Priarone et al. 2009). This research also studies the interaction of unbalanced and balanced energy loads, including borehole thermal energy storage (BTES) systems, with groundwater flow. Lastly, the effect of hydraulic heterogeneities is considered; while the earlier parts of the research only consider homogeneous settings. Heterogeneities introduced in this study are in the form of fractures discontinuities in a homogenous crystalline rock. They allow complex yet controlled levels of heterogeneity exclusively represented as discrete features while the dispersivity in the rock mass remains negligible. Past studies, such as Chiasson et al. (2000), Gehlin and Hellström (2003), and Liebel et al. (2012), have stated that fractures can affect the BHE loop temperatures, thermal response test (TRT) results, and apparent thermal conductivity of the ground. Here, it is intended to further examine the effect of fracture properties and complexity level of fracture networks on system performance and its impact.

1.2 Thesis organization

This thesis is structured in the integrated article format. The current chapter, Chapter 1, is meant to state the significance of this research and present the thesis outline. It also puts the appended papers in the context of study aims and illustrates the course of the research.

Chapter 2 is based on the manuscript, "*Guidelines and the Design Approach for Vertical Geothermal Heat Pump Systems: Current Status and Perspective*", currently accepted with minor revisions in the *Canadian Geotechnical Journal*. This chapter starts with a literature review on environmental and thermal sustainability of single and multiple borehole heat exchangers in a hydrogeological perspective. Of particular interest is the interaction of such systems with groundwater flow. Several recent studies (e.g. Lee and Lam 2009; Lazzari et al. 2010) have shown that the groundwater flux rates in the 10^{-7} m/s range (and above) impact the thermal response tests results (TRTs) and the performance of BHEs. Review of the software commonly used for the design of geothermal loops reveals that they dominantly overlook the advective heat transport by groundwater flow. This is despite the existence of coupled flow-heat transport software and the recently developed analytical solutions that account for advection (e.g. Diao et al. 2004; Molina-Giraldo et al. 2011). Finally, the current state of guidelines and regulations are reviewed, few of which mention the necessity for hydrogeological investigations and modeling or provide design recommendations.

Chapter 3 includes the paper, "*Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems*", accepted to the theme issue "*Hydrogeology of Shallow Thermal Systems*" of the "*Hydrogeology Journal*"(currently published as Online First Article). Knowing that high groundwater flow rates have an effect on the performance and impacts of the BHEs, this paper involves BHE models in different thermo-geological and hydrogeological circumstances with different borehole characteristics (groundwater flux, thermal conductivity of the ground, volumetric heat capacity of the ground, subsurface porosity, grout thermal conductivity, loop inlet and background temperatures), in the same modeling framework. Although various studies in the past have analyzed the effect of some of these factors individually (e.g. Hellström 1998; Chiasson et al. 2000), the main purpose of this work has been to enable us to compare them and distinguish the principal factors affecting BHEs. The results rank groundwater flux (above 10^{-7} m/s) and thermal conductivity of the ground as the top thermal-hydrogeological parameters affecting the performance and impact of BHEs. The temperature gradient between the antifreeze fluid and the ground is another key factor which implies accurate estimation of the ground temperatures to ensure a correct design. Groundwater flow clearly has a more significant role in returning the ground temperatures to the initial background temperature, i.e. thermal recovery. Groundwater fluxes as low as 10^{-8} m/s can accelerate the thermal recovery of the ground.

The manuscript submitted to the National Ground Water Association's (NGWA) *Groundwater* journal, "*Impact of Groundwater Flow and Energy Load on Multiple Borehole Heat Exchangers*", forms the 4th chapter. Previous studies such as Rybach and Eugster (2002), and Signorelli et al. (2005) have studied the effect of energy load and borehole spacing on the long-term sustainability of multi-BHE systems. The energy load balance (or unbalance) becomes more relevant as the number of boreholes increases. To our knowledge, no study has evaluated the effect of groundwater flow in conjunction with energy load balance. The evaluation is done for single, 2×1, 4×1, 2×2 and 4×4 arrays. This study also examines how important the borehole spacing is in this context. Based on the previous research a 10^{-7} m/s groundwater flux is assigned to models that include advection. The results show that groundwater flow has a larger impact on systems with unbalanced energy load which intensifies with time. Groundwater flow has an influence on energy balanced systems as well but it will remain relatively constant during their lifetime. Moreover, with an increase in the number of boreholes or switching from line to square array, i.e. intensification of loop and ground temperatures, groundwater flow becomes more important. The results demonstrate that the thermal interference between BHEs could be more significant in line arrays, relative to square arrays, if the groundwater flow direction is parallel to the array axis. Previous studies (Choi et al. 2013) have proven that line arrays are more sensitive to groundwater flow direction than square arrays are. The borehole spacing is also more influential on the efficiency of multi-BHE systems that have unbalanced energy loads. However, increasing groundwater flow shortens the time to reach quasi-steady state significantly more than increasing the BHE spacing does. Simulations confirm that, in the long-term, an array with smaller BHE spacing in a hydraulically conductive environment can over-perform a similar system with larger BHE spacing and no groundwater flow. Lastly, a borehole thermal energy storage (BTES) system is compared with a conventional multi-BHE system with balanced load. BTES systems essentially have a balanced energy load even though the building energy demand is not balanced, as they store the energy during one season for use at another time of year. In addition, typically BTES systems involve high temperature gradients which enhance the heat exchange by conduction. For this reason, groundwater flow exhibits a negative impact on the modeled BTES by increasing the stored energy while decreasing the energy extraction. Therefore, not integrating the groundwater flow in the design procedure of BTES systems can undermine their environmental and thermal sustainability.

The last paper, "*Effect of hydrogeological inhomogeneity on borehole heat exchangers*", which is prepared for submission to the *Bulletin of Engineering Geology and the Environment*, the official journal of the International Association for Engineering Geology and the Environment (IAEG), adds the heterogeneity aspect to the earlier homogenous models. The heterogeneity introduced here is in the form of fractures. Previous studies (e.g. Gehlin and Hellström 2003; Liebel et al. 2012) have proven that water-filled fractures nearby or intersecting a BHE can influence loop temperatures. This last paper aims to distinguish between heterogeneity features based on their properties and designate the principal fracture properties affecting BHEs. A BHE interacts differently with vertical and horizontal fractures. Vertical fractures can have different strikes (thus interconnect) and distances from the BHE, creating more complex heterogeneities. Horizontal features in this study will cross the BHE, and are restricted to be parallel to each other. Therefore, each of these features is studied separately. Although vertical fractures can form complex heterogeneity levels, our simulations show that one major fracture can be identified impacting the BHE based on their distance and fracture openness. The effect of vertical fractures on the BHE becomes progressively less as the distance between them increases. An open (1 mm) vertical fracture located up to 5 m away from the BHE significantly alters the loop temperatures; at 10 m distance the fracture still causes visible influence. Tight fractures (0.1 mm) have no noticeable influence but open (1 mm) and wide (10 mm) fractures will cause an obvious impact if located close enough to the borehole. While the impact increases considerably from a tight to open fracture, it increases substantially less from an open fracture to a wide one. Additionally, open fractures have the capacity to reduce the thermal inference among adjacent BHEs if passing between them. Simulations also prove that while a standard thermal response test (TRT) may not be able to detect some nearby vertical fractures, they affect the long-term efficiency of the BHE. This suggests that TRTs are less effective in such highly heterogeneous environments. In fractured rock sites, where the rock mass has more or less constant thermal properties, a TRT or perhaps simpler thermal conductivity measurement methods such as probes, could be combined with site investigation techniques like fracture mapping or geophysical measurements.

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Chapter 2

2 Guidelines and the Design Approach for Vertical Geothermal Heat Pump Systems: Current Status and Perspective

2.1 Introduction

Shallow low temperature geothermal (alternatively called ground source, ground coupled, geoexchange and earth energy) systems utilize normal ground temperatures and are generally used for space heating and cooling. This temperature range allows such systems to be used worldwide. These systems rely on the nearly constant temperature of the subsurface throughout the year. Fluctuations in ground temperature decrease with depth (Rosén et al. 2001, Banks 2008) due to the high thermal inertia of the soil, the time lag between temperature variations at the surface and in the subsurface (Florides and Kalogirou 2007) and the upward geothermal flux from Earth's center. Seasonal temperature variation diminishes below the depth of ca. 10 m according to Anderson (2005). The exact depth depends on the ground thermal properties, varying from 8 m for dry light soils to 20 m for moist heavy sandy soils (Popiel et al. 2001). Temperatures at such depths are similar to the average ambient air temperature over the year (Ochsner 2007). The ground temperature above this depth is affected by land cover (Ferguson and Woodbury 2007) and weather (Zhang 2005, Florides and Kalogirou 2007). As in summer/winter the subsurface temperature is respectively lower/higher than the air temperature, the ground source heat can be employed to cool/heat the buildings.

In open loops the energy extraction process occurs through the enhanced artificial advection of groundwater by pumping wells. Geothermal vertical closed loop systems extract energy only through heat exchange with the geologic media and the groundwater. Closed loops are commonly preferred due to less environmental interference, no need for the direct consumption of water resources, and an often reduced regulatory environment (Banks 2008). Geothermal loops can have other serious hydrogeological impacts, such as breaching aquitards and exposing aquifers to pollutants and enhanced salinity. Vertical closed systems are installed in boreholes typically 100-150 m deep which is limited by the commonly used polyethylene pipe (diameters/frictional losses) and drilling costs. In Switzerland installations to a depth of 500 m using 50 mm diameter polyethylene pipe have been reported. If long borehole lengths are required, it is more feasible to use multiple boreholes to avoid deep drilling/installation complications and increase the energy extraction area as closed loops function only on conduction.

Closed loop ground heat exchangers are alternatively termed as ground coupled heat exchanger (GCHE) and ground source heat exchanger (GSHE); specifically vertical closed loops also are known as borehole heat exchanger (BHE). Since ground heat exchangers should effectively exploit the ground heat for long periods of time due to their high initial installation cost, they should have good thermal properties and durability. Highly durable and flexible polyethylene and polypropylene are typically used in production of ground heat exchangers. Most borehole heat exchangers consist of U-pipes, with a U-turn in the end creating a loop: single U-pipe (e.g. common in Canada and Sweden) or double U-pipe when two U-pipes are inserted in the borehole (e.g. common in Germany and Switzerland). The other, less common, type includes coaxial pipes or concentric heat exchangers. Depending on the direction of the flow this type of heat exchanger can be with annular (CXA) or centered (CXC) inlet (Diersch et al. 2011a). Schematics of different heat exchangers are shown in Figure 2.1.

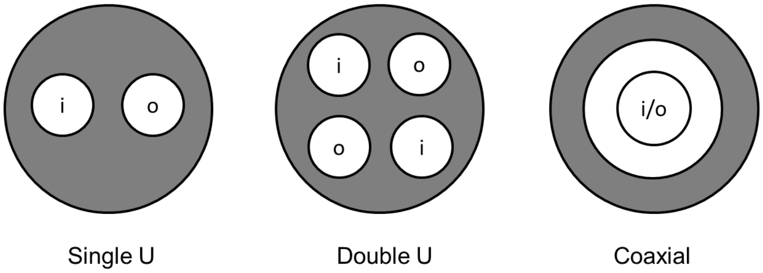

Figure 2.1 Schematics of U, 2U and coaxial borehole heat exchangers. Grey color illustrates the grouted zone; white color shows the tube. Letters i and o stand for in and out respectively.

A circulating fluid or heat transfer fluid, usually a water-antifreeze mixture, is used to extract the heat and transport it in the system. An antifreeze is evaluated based on factors like thermal properties, viscosity and lifetime pumping costs, toxicity, biodegradability (aerobic and anaerobic), biological oxygen demand (BOD), corrosivity and flammability (refer to Heinonen et al. (1997, 1998) for more details).

The gap between the BHE and the borehole wall, i.e. annulus, is usually filled with grout. This reduces the thermal efficiency of the BHE but protects the groundwater from antifreeze leakage, introduction of contaminants from the surface, and interconnected aquifers. For example, improper grouting in Staufen im Breisgau, Germany exposed a anhydrite sulphate calcium layer to water; causing damage to more than 250 houses (Oriol 2010 after Therin 2010). In North America and most parts of Europe the annulus is grouted (Andersson 2007, Denicer and Rosen 2007) while under certain geological conditions, like in parts of Scandinavia (e.g. Sweden's *Normbrunn - 07*), grouting is not required and the boreholes are naturally filled with groundwater leading to increased thermal efficiency of the system and extended borehole life. The not-grouting practice has other long-term economic benefits by making the borehole reusable beyond the life of the loop pipes. However, this is possible due to the presence of hardrock geology with minor soil cover. When grouting is to be done, using thermally enhanced grout is recommended due to its lower thermal resistance.

The simplest technique for using ground source heat is to circulate the heat exchanger fluid in the building, called free or passive cooling/heating. However, geothermal heat pumps (GHPs) are normally used in conjunction with BHEs, to lift or sink the gained temperature differential by using electric power. Geothermal heat pumps are also called ground source heat pump (GSHP) and ground coupled heat pumps (GCHP).

Underground thermal energy storage (UTES) is the process of storing the thermal energy under the ground by disturbing the natural ground temperatures for future use on a seasonal basis. UTES systems are used to store natural and waste energy, shift the periods of peak energy demand and enhance the heat exchange process. In aquifer thermal energy storage (ATES) systems thermal energy is stored in the groundwater and in the soil/rock matrix through an open loop. Borehole thermal energy storage (BTES) is a UTES practice using a number of densely spaced closed loop BHEs.

2.2 Aim of Study

This study begins with a brief review on the state of research on the sustainability of geothermal heat pump systems with concentration on the thermal and thermally driven environmental issues. The main purpose of the literature review is to address the influence of groundwater flow on geothermal systems and identify any known thresholds where advective heat transport is no longer negligible. The available loop design tools which are commonly used by the industry will be explored. Furthermore the method employed by design software is examined particularly with regards to assumptions on groundwater flow. Finally the current state of regulations is reviewed, and the potential for integrating the groundwater flow in vertical geothermal systems is considered. Since open loops involve the extraction of groundwater and have potentially larger environmental implications, typically they require more intensive hydrogeological evaluations and trigger more regulatory provisions. On the other hand, closed systems often fall outside the typical groundwater regulatory environment. They also are often designed without consideration of groundwater advection. Thus while open loop systems are covered in this paper for comparison, the focus is on closed loop systems.

As the following review will show, under certain conditions where groundwater flow rate is sufficiently high, a lack of consideration for groundwater advection can lead to considerable difference between actual and designed system performances. Although comparable reviews have been done on the state of regulations (e.g. Haehnlein et al. 2010) or design (e.g. Hellström and Sanner 2001), this paper attempts to bring the legislation, design tools and knowledge aspects together and point out the deficiencies in that context. Recognition of the role groundwater plays in thermal design and environmental impact of a GHP system will be evaluated by reviewing the state of regulations in some of the more advanced jurisdictions. The potential for the present state of research to contribute to more sustainable designs is also assessed. Lastly this review intends to improve the current regulatory and design situation in Canada by putting it in an international perspective and increasing the awareness among the associated Canadian authorities and professionals.

This work does not address if the cited information is legally enforced or only voluntary. Thus the use of terms such as recommendation, guideline, standard, regulation and legislation are intended to reflect the proper context but may not in all cases.

2.3 Design and environmental-thermal sustainability in a hydrogeological context

Historically major concerns with geothermal heat pump systems involved the mechanical components and design, energy efficiency, and cost. However, recently their interaction with subsurface processes and protection of underground resources, chiefly groundwater, is receiving increasing attention. Concerns about GHPs are not only environmental, but also include thermal performance and sustainability of the system (Ferguson and Woodbury 2005, Hecht-Méndez et al. 2010). Although some of the impacts are similar to those involving water wells, this work focuses on thermally driven subsurface impacts including impacts on adjacent systems. While heat can be recognized as pollution (e.g. *European Water Framework Directive*), with the exception of a few countries, current standards and regulations do not address thermal pollution.

Geological material, through their thermal properties, influence the performance of ground coupled systems. Saturation of porous media by groundwater – not flowing – improves its thermal properties as the air is replaced by water. Groundwater hydraulics also affects the thermal functionality of a system as groundwater flow can significantly alter heat transport. Andrews (1978) was one of the first to study "*The Impact of the Use of Heat Pumps on Ground-Water Temperature*". Heat anomalies can have physical (Schincariol and Schwartz 1990, Kolditz et al. 1998, Hecht-Méndez et al. 2010), chemical (Sowers et al. 2006, Renac et al. 2009) and biological (York et al. 1998, Gordon and Toze 2003, Sowers et al. 2006, Markle and Schincariol 2007, Brielmann et al. 2009) impacts. These aspects can be interrelated; Banks (2008) discusses the effect of temperature change on chemical equilibrium in limestone aquifers which affects the physical hydrogeological aspects such as permeability and porosity. Thermal alteration can also affect the biology of groundwater directly or through its aquatic chemistry which can in turn influence the physical hydrogeology in extreme cases (*VDI 4640 Part3*).

Since the early 20th century many models have been developed that are used to simulate borehole heat exchangers by authors such as Allen (1920), Ingersoll et al. (1950, 1954), Carslaw and Jaeger (1959), Eskilson and Claesson (1988), Hellström (1991), Kavangaugh (1992), Zeng et al. (2002), Al-Khoury et al. (2005), Lee and Lam (2008) and Zhongjian and Maoyu (2009). The results presented by Hellström (1998) and Acuña and Palm (2009) indicate that in-borehole setup (i.e. pipe configuration and fill) have significant impact on borehole thermal resistance. The impact of proximal systems on each other is multiplicative in terms of thermal efficiency. For example in Lyon, France, multiple open loop systems have increased the groundwater temperature by 3-4 °C, where each system is believed to have 1 °C impact; in a likely and plausible future scenario, groundwater temperature may exceed 25 °C resulting in non-potable water and conflicts in use (Oriol 2010). Ferguson and Woodbury (2006, 2007) show that urban and geothermal development can cause a large scale subsurface temperature increase. Similar phenomena can happen with closed loop systems (e.g. Signorelli et al. 2005) and requires concern.

Rybach and Eugster (2002) evaluated the sustainability of a single BHE. Signorelli et al. (2005) expanded their work to multiple boreholes; concluding that for 6×100 m deep borehole field, with no seasonal heating/cooling recharge, 15 m spacing is completely sustainable while with 5 m spacing boreholes strongly influence each other. They also show that borehole spacing is a function of borehole depth (i.e. specific heat extraction) with efficiency increasing with deeper boreholes. The thermal recovery time, during which subsurface temperatures return back to the initial background values after shutting down a system, equals that of operation for a single BHE, and can be almost twice as long for multiple borehole fields (Signorelli et al. 2005). Later, Priarone et al. (2009) studied performance of single and multiple BHEs without and with complete seasonal recharge. They conclude that for a single BHE seasonal recharge is not necessary; while in a field of four BHEs 50% recharge, and in an infinite field, 100% seasonal recharge is needed to ensure the long-term sustainability of the system.

Kavanaugh and Calvert (1995) and Kavanaugh and Rafferty (1997) suggest equations and correction factors applicable to different load cycles, grids and borehole separations. All the above cited studies assume the absence of groundwater flow. Chiasson (1999), Spitler et al. (1996) and Austin et al. (2000) show that increasing groundwater velocity increases effective ground thermal conductivity. One common method to measure the ground apparent thermal conductivity is a thermal response test (TRT). Traditionally the analysis of TRT results has been done assuming heat transport by conduction only. However studies such as Wagner et al. (2013) have extended the applicability of advection influenced TRT beyond a Darcy velocity of 0.1 m/day (1.15×10^{-5} m/s). Although performing a conventional TRT accounts for groundwater advection in estimating the apparent thermal conductivity, not including the flow rate and direction makes it impossible to accurately model the interaction between BHEs in a field as well as adjacent fields. Research by Gehlin (2002) concludes that groundwater flow changes temperature in and around a borehole in fractured as well as porous media. Diao et al. (2004) developed an analytical solution for a line heat source in an infinite medium which accounts for groundwater advection. Their results showed that advective transport by groundwater may alter the temperature distribution, lower temperature disturbances and eventually allow for the reaching of steady state conditions compared to a conductive dominated regime. According to a similar study by Fuji et al. (2005), Péclet numbers higher than 0.1 enhance the heat extraction rate. Lee and Lam (2009) observed and estimated the influence of groundwater velocity on TRT results at velocities over 2×10^{-7} m/s. Numerical modeling of two arrays of three and six BHEs by Lazzari et al. (2010) concludes that a groundwater velocity of 10^{-7} m/s suffices to stabilize the loop temperatures after a few years. Dehkordi and Schincariol (2013) found that groundwater fluxes above 10^{-7} m/s and 10^{-8} m/s to have a noticeable impact on improving the BHE temperatures during operation and recovery, respectively. Diersch et al. (2011b) simulate a BTES system and address the effect of groundwater flow on efficiency and reliability of such systems. Their results show small, but significant, temperature changes may occur downgradient which suggests the need for long-term evaluations in environmental studies.

Groundwater flow can make a BHE system more efficient, requiring a shorter heat exchanger and allowing for a longer sustainable heat extraction period by enhancing heat transfer (Wang et al. 2012). Groundwater flow is particularly undesirable for underground thermal energy storage (UTES) systems (Bauer et al. 2009). Some of the common "loop design" software (Table 2.1) include the thermal properties of the ground but usually exclude the groundwater movement (e.g. *EED*, *GLHEPRO* and *GeoAnalyser*). Therefore current designs may not always be optimal. In a dynamic hydrogeological environment, the shape and transport of the heat plume may be less understood, and the impact on adjacent systems is more uncertain. Coupled groundwater flow and heat transport models are available (Table 2.1) but are more commonly used for flow and transport studies and not the design of BHEs. However, some studies such as Nam et al. (2008) employed groundwater coupled models instead of those based solely on conduction.

2.4 International status of the related guidelines

Forty years ago only 10 countries were using geothermal energy in any form but today that number has increased to 80 and expected to increase to 90 by 2015 (Lund and Bertani 2010). Studies show an increase in the use of GHP systems, especially in the EU and US, even in regions with low potential for conventional geothermal resources (Freeston 1995, Lund and Freeston 2000, Sanner et al. 2003, Lund et al. 2004, Banks 2008). It is one of the fastest growing renewable energy forms; with an average annual growth of more than 10% (Bertani 2005, Curtis et al. 2005, Lund et al. 2005).

At the international level virtually no mandatory guidelines exist. Guidelines such as "*Closed-loop/Geothermal Heat Pump Systems – Design and Installation Standards*" by the International Ground Source Heat Pump Association (IGSHPA 2010) or some of the better national standards available (to be discussed later in this paper) may become accepted or simply followed by professionals in countries which do not have their own GHP regulations. According to Sanner (2008), European standards (i.e. *EN 15450*, the

Table 2.1 Typical computer codes used in geothermal systems. Mainly after: Hellström and Sanner (2001)[*], Anderson (2005)[†], EU Commission SAVE Programme & Nordic Energy Research (2005)[‡], Hecht- Méndez et al. (2010)[§], Yang et al. (2010a)[‖].

Heat transport	Loop design	UTES design
AST/TWOW [§]	CLGS [*]	AST [‡]
BASIN2 [†§]	DIM [*]	ConFlow [‡]
COMSOL Multiphysics (formerly FEMLAB) [§] Acuña and Palm (2009), Priarone et al. (2009)	ECA [*]	COSOND/NUSOND/TRAD [‡]
FEFLOW [†‡§]	EED [*‡‖]	DST [‡]
FRACHEM [§]	GchpCalc [*‖]	EED
FRACture [§]	GeoAnalyser (by CGC)	FEFLOW
GeoStar [‖]	GEOCALC [*]	GHS [‡]
GeoSys/RockFlow [§]	GeoDesigner (by Climate Master)	HB-MULTIFIELD [‡]
HEATFLOW [†§]	GLHEPRO [*‖]	MODFLOW [‡]
HEAT2, 3 Blomberg (1996)	GL-Source [*]	HST2D/3D
HST2D/3D [†‡§]	GS2000 [*]	PIA12[‡]
HydroGeoSphere (based on FRAC3DVS) [§]	INOUT *	PHREEQM-2D [‡]
HydroTherm [§]	Right-Loop [*]	SBM
HYDRUS 2D/3D [§]	TFSTEP [*]	SHEMAT
ParFlow [§]	WFEA [*]	SmartStore [‡]
SBM [*‡]		SPREADSTO-1 [‡]
SEAWAT [§]		TECOCLAY [‡]
SHEMAT [†‡§]		THETA
SUTRA [†§]		TOUGH2
THETA [‡§]		TRADIKON-3D
TOUGH2 [†‡§]		TRNSYS-DST, TRNAST, EWS, SBM [*‡]
TRADIKON 3D [‡§]		TWOW [‡]
TRNSYS with DST-module [‡]		
VS2DH [†§]		

European standard for the design of heat pump systems) only provide a minimum framework because of the geological and climatic disparities, and heating and cooling traditions, that exist between the countries. For instance in Europe most systems are often undersized and designed for base heating load while the peak load is supplied by alternative sources (Curtis et al. 2005, Sanner and Boissavy 2007); whereas in the US systems are designed for peak cooling load and oversized for heating (Banks 2008, Lund and Bertani 2010). Nevertheless, European standards are valuable in that they provide a general framework to guarantee at least a basic level of quality assurance in the European countries. On this basis, domestic standards for each country can be developed based on the local conditions. In many countries installation of open loops lie under water well regulations, while closed loops are not regulated because they do not extract water from the subsurface; in other cases there may be exclusive legislations for closed and open systems (e.g. Denmark) or both water and energy wells can be covered under similar regulations (e.g. Sweden).

In countries that have established regulations on the thermal use of the shallow subsurface, common control mechanisms to minimize adverse impacts include defining limits for the borehole depth; distance between boreholes; distance to: drinking water extractions, potential contamination sources, property borders, buildings, roads, and pipelines. In some cases temperature limits are also defined: absolute minimum and maximum subsurface temperature, temperature difference from the altered and natural background temperatures, inlet and outlet temperatures. Some guidelines provide instruction on specific heat extraction and probe length design (e.g. Swiss *AWP T* and German *VDI 4640*, *ASHARE*) to ensure a minimum level of sustainability (Table 2.2). Outside the scope of this study, guidelines may also cover other factors like antifreeze, grout, pipe material, and their installation, water quality, system size (e.g. depth, flow rate, heat capacity and rate), heat pump coefficient of performance (COP) and energy efficiency, insulation and monitoring. Below is a summary of ground heat use along with the related guidelines in different countries. Corresponding temperature and distance limits are presented in Tables 2.3, 2.4 and 2.5.

Table 2.2 Allowable heat extraction rates under German and Swiss regulations based on soil type, moisture content and full load operation hours per year.

	Loop type	**Underground conditions**	**Specific heat extraction**			***Reference***
			1800 hr/yr	**2400 hr/yr**	**>2400 hr/yr**	
Germany	Vertical <30 kW, heating only	Poor underground (dry sediment) λ < 1.5 W/(m.K)	25 W/m	20 W/m	100-150 kWh/m per year	*VDI 4640*
		Normal rocky underground and water saturated sediment λ < 1.5–3.0 W/(m.K)	60 W/m	50 W/m		
		Consolidated rock with high thermal conductivity λ > 3.0 W/(m.K)	84 W/m	70 W/m		
			1800-2000 hr/yr	**Remarks**		
Switzerland	Vertical <30 kW, heating only	Saturated strata (λ > 3 W/(m.K)	80 W/m	Plants with more than three boreholes have a lower withdrawal performance. Bivalents or other plants with high annual periods (> 2000 hours) have a lower extraction capacity (W/m); max 80-100 kWh/m Lower efficiency in mountain regions 30 W/m cooling capacity		*AWP-T*
		Rock and moist soil (λ > 2 W/(m.K)	50-55 W/m			
		Dry soil (λ < 1.5 W/(m.K)	30 W/m			

Table 2.3 Temperature thresholds of vertical closed loop geothermal systems.

Country	Min (°C)	Max (°C)	Change (°C)	*Reference*
Austria	0 with mean load 5 with peak load	35	15	*Haehnlein et al. 2010*
Canada	0 inlet; for small residential systems	-	1 in UTES	*CAN/CSA-C448-02*
Denmark	2	-	-	*BEK nr 1019, 25/10/2009* *BEK nr 1206, 24/11/2006*
France	-	-	-	*Haehnlein et al. 2010*
Germany	-	-	11 with weekly average base load 17 with peak load	*VDI 4640*
Italy	-		Lombardi: 3-5	*Banks 2008*
Liechtenstein	-	-	-	*Haehnlein et al. 2010*
Sweden	-	-	-	*Normbrunn -07*
Switzerland	2 return temperature for ponds	-	3-5 for cooling	*AWP T1-5*
UK	-	-	10 between mean loop and background temperature	*Energy Efficiency Best Practice in Housing*
US	-	-	3-7 between inlet and outlet	*2007 ASHRAE Handbook – HVAC Applications, Chapter A32: Geothermal Energy*
Others	5	-	-	*Signorelli et al. 2004*

Table 2.4 Distance thresholds for vertical closed loop geothermal systems.

To building	To next property	To roads	Between boreholes	Depth	Diameter	Country
-	2.5 m	-	-	-	-	**Austria**
				>5 m regulated by O. Reg 98/12		**Canada**
-	-	-	3-6 m	-	-	**China**
-	5 m	-	-	-	-	**Czech Republic**
-	-	-	20 m	-	-	**Denmark**
3 m	10 m	-	-	-	-	**Finland**
-	-	-	-	<100 m and the maximal heat rate is <232 kW, exempt from permit but a declaration still needed for >10 >100 m and/or larger than 232 kW, authorization required	-	**France**
2 m	Hessen: 5 m Schleswig-Holstein: 6 m	-	in order to use guideline for <30kW heating 5 m for 40-50 m deep 6 m for 50-100 m deep	-	-	**Germany**
-	-	If outside a city plan: 60 m from the motorway 45 m from the national road 20 m from provincial road 6 m from municipal road	-	-	-	**Greece**
4 m	10 m	-	20 m (in rock)	-	-	**Sweden**
-	3-4 m	-	5-8 m	-	-	**Switzerland**
1.5 m		-	3-5 m	-	-	**UK**
-	Massachusetts: 3 m (10') NGWA: 6 m (20')	-	ASHRAE: 4.5-8 m (provides m/kW based on heating/cooling load, plus additional correction factors for different grids) NGWA: 6 m (20')	Missouri: 3-70 m (deeper than 10' are regulated and deeper than 200' are not normally allowed)	Missouri: depends on pipe and grout New Jersey: borehole diameter =inner tube diameter+outer tube diamtere+4" NGWA: dependent on depth	**USA**
Oriol 2010: 6 m			*Signerolli et al.2005*: 15 m (no seasonal recharge) *Oriol2010*: 10 m *Priarone 2009*: 6 m (4 boreholes with 50% seasonal recharge or infinite boreholes with complete seasonal rechanrge) *Ochsner 2007*: 5 m			**Others**

Table 2.5 Distance thresholds for vertical closed loop geothermal systems (continuted).

Discharge	to facilities, pipelines and powerlines	To waste, sewage and other contaminant sources	To surface water bodies	To drinking water wells	Country
	-	-	-	-	**Austria**
					Canada
	-	-	-	-	**China**
	-	-	-	-	**Czech Republic**
	-	-	-	300 m (50 m from own water supply)	**Denmark**
	5 m	30 m (20 m if onsite)	-	20 m (dug) 40 m (bored)	**Finland**
>8 m^3/h only a declaration, >80 m^3/h authorization is required too provided that withdrawn from and discharged into the same aquifer, even if shallower than 10 m	-	-	-	-	**France**
	cold part 0.7 m from any water supply or disposal pipes to avoid freezing	-	-	-	**Germany**
	-	-	-	-	**Greece**
		30 m		20 m (in soil) 30 m (in rock)	**Sweden**
	-	-	-	-	**Switzerland**
	-	-	-	-	**UK**
	Massachusetts: 3 m (10')	NGWA: 3-30 m (10', 25' or 100' depending on contamination) Massachusetts: 7.5 m (25') Mississippi: 30 m (within 100' must be grouted) Missouri: 15-100 m (50', 100' or 300' depending on the contamination)	Massachusetts: 30 m (10') Massachusetts: 30 m (100') from wetlands need permit	Illinois: 70 m (200') 75' from own water well) Massachusetts: 15 m (50') Missouri: 15 m (50')	**USA**
	Oriol 2010: 1.5 m	*Oriol 2010*: 6 m	-	*Oriol 2010*: 6 m (non-public), 30 m (public)	**Others**

Table 2.6 Distance thresholds for vertical closed loop geothermal systems (references).

Reference	**Country**
Haehnlein et al. 2010	**Austria**
CAN/CSA-C448-02 *O. Reg 98/12*	**Canada**
Haehnlein et al. 2010	**China**
Haehnlein et al. 2010	**Czech Republic**
BEK nr 1019, 25/10/2009 *BEK nr 1206, 24/11/2006*	**Denmark**
Haehnlein et al. 2010	**Finland**
Ground Reach, 2008 *Oriol, 2010*	**France**
VDI 4640 blatt 1 *Ground Reach, 2008*	**Germany**
No Δ9Β, Δ/Φ166/OIK *18508/5552/207* *EGEC 2008* *Haehnlein et al. 2010*	**Greece**
Normbrunn 07 *Ground Reach, 2008*	**Sweden**
AWP T 1-5	**Switzerland**
Domestic Ground Source Heat Pumps: Desing and installation of closed-loop systems	**UK**
ASHRAE handbook *Illinois Administrative Code - Title 77, Chapter I, Part 920* *Massachusetts Guidelines For Ground Source Heat Pump Wells* *Mississippi Commission on Environmental Quality Regulation LW-2 and LW-3* *Missouri Code of State Regulations - Title 10, Division 23, Chapter 3 and Chapter 5* *NGWA 2010bs* *Utah Administrative Code, Rule R655-1.* *Utah Code, Title 73, Chapter 22* *Washington State University Extension Energy Program*	**USA**

Table 2.7 Temperature thresholds of BHE and open loop geothermal systems.

Country	Open loop			*Reference*
	min (°C)	max (°C)	change (°C)	
Austria	5	20	6	*Haehnlein et al., 2010*
Canada	5 inlet; for small residential systems	-	-	*CAN/CSA-C448-02*
Denmark	2	25 20 with monthly average	-	*BEK nr 1019, 25/10/2009* *BEK nr 1206, 24/11/2006*
France	-	-	11	*Haehnlein et al., 2010*
Germany	5	20	6 between inlet and outlet	*VDI 4640 blatt 1* *VDI 4640 blatt 2* *VDI 4640 blatt 3* *VDI 4640 blatt 4*
Liechtenstein	-	-	1.5-3	*Haehnlein et al., 2010*
Netherlands	5	25		*Haehnlein et al., 2010*
Switzerland	4 return temperature	-	3-5 for cooling	*AWP T1* *AWP T2* *AWP T3* *AWP T4* *AWP T5*

2.4.1 Austria

Use of ground heat systems was initiated in 1976; steadily increasing since late 90's with a tremendous growth rate of 37.7% in 2005-2006 numbering to 49,600 (Ground Reach 2008). Austrian standards directly applicable to GHPs in the context of this paper are *ÖNORM M 7755-1* on general requirements, *ÖNORM M 7755-2* on ground, groundwater and surface water systems and *ÖWAV RB 207* on thermal use of groundwater and underground heating and cooling.

2.4.2 Belgium

In Belgium knowledge of GHP systems is low and this has hindered development of the technology according to Ground Reach (2008) who state: "*A great barrier for GCHP-systems consists in the lack of knowledge of these systems…. HVAC installers consider heat pumps as a difficult technology*". Belgium requires a drilling permit for vertical open and close loop systems (Ground Reach 2008). The Belgian standard, environmental legislation *VLAREM*, was changed in September 2011 in regards to the construction of vertical boreholes (VITO 2013) prior to which geothermal boreholes deeper than 50 m required a permit (DOV 2013a). The updated legislation makes the depth criterion location dependent; online maps are provided to find the appropriate depth criterion in Vlaanderen (Flanders) region (DOV 2013b).

2.4.3 Canada

In Canada, GHPs are the main source of geothermal energy (Lund and Bertani 2010). According to the Canadian GeoExchange Coalition (CGC) (2010a), during the early 90's more than 7000 residential units were installed in Canada; the annual number of installed units hit a 20 year historic low in 1998. Between 2004 and 2008 the ground source heat pump market has grown by 50% annually. A strong factor in this growth is likely government financial support together with a nationwide initiative led by CGC to provide quality assurance and promote the technology (CGC 2010a). However, this $500 million industry (as of 2009) is believed to have a penetration rate of less than 0.5% in the HVAC sector CGC (2010a) leaving a great deal of room for future expansion. Based on statistics from CGC (2011), which tracks mostly domestic installations, horizontal loops dominate Canadian installations at around 56% while the share of vertical loops is 24% between 2008 and 2010. The statistics for Ontario are 65% and 15%, respectively, during the same period.

Currently there are no specific federal laws on subsurface heat extraction. While provinces maintain jurisdiction over natural resources (*Canadian Constitution Act*) there are instances where existing federal legislation could affect geothermal energy resource development. For example, if a GHP impacted fish or fish habitat, then provisions of the federal *Canadian Fisheries Act* or the federal *Canadian Species at Risk Act* would apply.

At the provincial level changes have been underway in many provinces to amend their groundwater and wells acts to better address geothermal installations. Ontario has legislation that governs GHPs, or Earth Energy Systems as they are commonly referred to, both indirectly and directly. The *Ontario Water Resources Act (OWRA)* does not specifically mention GHPs, but as open loop systems are water wells they fall under *OWRA Regulation 903* which covers all aspects of well construction, permitting, abandonment, and contractor/technician licencing. Often installers of BHEs were not as qualified to handle difficult drilling conditions (e.g. artesian aquifers, blowouts) and major environmental or human impacts can occur. Such was case in Ontario when an installer of a vertical closed loop geothermal system hit a natural gas pocket at a depth of approximately 165 m. Ontario responded by developing *Ontario Environmental Protection Act O. Reg. 98/12* which became law as of May 18, 2012. Under *O. Reg. 98/12* an Environmental Compliance Approval under section 9 of the *Ontario Environmental Protection Act* is required for any vertical closed loop geothermal system that extends more than 5 m below ground surface. The application for environmental compliance approval must be prepared by a licensed engineering practitioner or professional geoscientist. In *British Columbia*, as of 2005, closed loop geothermal wells are covered in the *Ground Water Protection Regulation* under the *Water Act* from construction and maintenance to the deactivation at the end of their service. If the well reaches an aquifer or is deeper than 50 feet, it must be constructed by a qualified well driller or under the supervision of a qualified professional engineer or geologist. When constructing a closed loop geothermal well, a 3 ft. surface seal is required. The decommissioning must be done within 90 days by filling the well throughout its entire depth with a sealants-backfill combination. However, disposal of water from open loops is considered as low risk and requires no authorization. Use of a dye is recommended in closed loops to show any possible leakage; but it is stated to be unlikely due to the build quality of the heat exchangers. In *Nova Scotia* under the *Mineral Resources Act* the Governor in Council may designate an area as a geothermal resource (including conventional geothermal) thereby making provisions of the Act applicable. In *New Brunswick's Regulation 2000-47* under the *Clean Water Act*, wellfield protection areas, in which use of geothermal heat pumps is prohibited, are designated to protect the public water supply. In 2012 Manitoba revised the *Manitoba Groundwater and Water Well Act* to require licensing and certification of geothermal drillers and directly apply the Act to closed loop geothermal systems. Some municipalities have also passed by-laws or restricted the development of GHPs. For example Waterloo, ON has included prohibition of GHP systems in its official plan to protect groundwater supplies; North Grenville, ON prohibited any GHP installation within one subdivision without a hydrogeological report (Brodie-Brown 2010).

The Canadian Standards Association (CSA), a not-for-profit standards organization, has also developed standards for GHP systems. These voluntary standards can become enforceable when referred to such as in the *Ontario Building Code Act* which refers to *CAN/CSA C448-02* "*Design and Installation of Earth Energy Systems*". While the Province of Ontario is responsible for the development and amendments to the Code, enforcement is a municipal responsibility. The *CSA C448-02* consists of three parts: earth energy systems commercial and institutional buildings, residential and other small buildings, and underground thermal energy storage systems for commercial and institutional buildings. It covers both open and closed loop systems. The *CSA 448.1-02* (section on commercial systems) states vertical open and closed loop conditions should be assessed by a hydrogeologist; however, no guidance on the evaluation process or parameter values is provided other than relying on professional judgement. For open loop systems, stratigraphy, groundwater level, chemical and physical characteristics, temperature profile, water yield and recharge rate, and water samples shall be recorded;

monitoring wells are also recommended. For vertical closed loops, depending on the building size, a number of test boreholes maybe needed, if potable water is likely to be encountered. Minimum heat exchanger lengths are provided for residential systems. The design should be done for over a 10 year modelling period only – which is rather short considering usual system life times. According to *CSA 448.1-02* main concerns regarding UTES systems are groundwater contamination and thermal effects on groundwater resources. Knowledge of the groundwater flow direction and velocity is required to be documented for maximum system retention time and efficiency but not explicitly for thermal pollution of surrounding systems – which is equally important. However it is mentioned that the temperature change of groundwater extracted by neighbors should not be "unacceptable". Finally, one major drawback of using building codes, whose primary responsibility is to minimize the risk to health and safety of building occupants and ensure building energy efficiency, is the fundamental disconnect with offsite ground and environmental conditions.

While GHP regulations are sparse in Canada there is a move to remedy this. As mentioned previously some provinces have updated their legislations to directly address GHPs. Furthermore, at the federal level, the CGC has prepared a manual "*Design and Installation of Residential Ground Source Heat Pump Systems*" (CGC 2010b). The manual is aimed at the Canadian GHP industry, including colleges and universities, and is used for educating installers and residential designers as part of CGC's national quality program.

2.4.4 Denmark

GHP systems have been used in Denmark since the 1970's (Ground Reach 2008);while there are approximately 55,000 heat pump systems (air and ground source) installed, they represent less than 1% of the total heating energy in Denmark (Ground Reach 2008, The official website of Denmark 2011). Danish regulations *BEK nr 1019 af 25/10/2009* and *BEK nr 1206 af 24/11/2006* cover utilization of ground and groundwater energy through closed and open loops. These regulations are perhaps one of the strictest guidelines currently in existence. A permitting process is in place for GHP systems and both distance and temperature limits are imposed; municipal councils can make the requirements even stricter. Violating the requirements can lead to imprisonment for up to 2 years. The enforced limitations on modelling and monitoring requirements of open loops are conceivably stricter. In particular a modelling study is required to show that the groundwater temperature will not increase by more than 0.5 °C in the existing water supply and cooling systems. Borehole heat exchanger fluid volume and inlet and outlet temperature must be automatically monitored, recorded and reported to municipal council.

2.4.5 France

France places 3rd in the European GHP market (Oriol 2010). In France geothermal resources fall under mining law and require licensure. Low temperature geothermal resources fall within the category of low enthalpy geothermal deposits (below 150 °C) and permitting is required under *Decree 77-620* and *78-498* (MVV 2007, Ground Reach 2008). In the French regulatory framework, if the depth is less than 100 m and the maximal heat rate release is less than 232 kW, the system is exempt from permit requirements but a declaration is still needed for drilling deeper than 10 m (Ground Reach 2008, Oriol 2010). For installations deeper than 100 m and/or larger than 232 kW, an authorization is required (Ground Reach 2008, Oriol 2010). Open loop systems are covered under water law by *Decree 64-1245*. For geothermal use groundwater extraction of more than 8 m^3/h only requires a declaration, while for more than 80 m^3/h authorization is required (MVV 2007, Ground Reach 2008), provided that it is withdrawn from and discharged into the same aquifer, even if drilling shallower than 10 m (Oriol 2010).

Ground Reach (2008) found that legislation for BHEs was not well defined in France. In 2011 new standards *NF X10-970* have been introduced for vertical ground geothermal closed systems covering installation, use, maintenance and abandonment. The major points included are the biodegradability of the refrigerant, environmentally sound ground, grout conductivity in relation to soil, borehole diameter in relation to depth, and general rules for sizing depending on the site geology. Open loop systems are covered under the standards *NF X10-999* and *FD X10-980*. The potential adverse environmental impacts of GHPs are under study by the French Geological Survey (BRGM) (Oriol, 2010).

2.4.6 Germany

Low temperature geothermal energy is widely used for space heating in Germany (Schellschmidt et al. 2010) with large capacity operating in the commercial sector (Curtis 2005). By the end of 2009, GHPs installed in Germany numbered178,000, ranking it second in Europe in terms of number of installations (EGEC 2008, Schellschmidt et al. 2010). A certificate of drilling may be required for drilling shallow geothermal boreholes (MVV 2007). German GHP related laws are applied at two levels: federal (Bund) and states (Länder) (e.g. Bayern, Baden-Württemberg, Berlin, Hessen, Nordrhein-Westfalen, Rheinland-Pfalz); municipalities may also apply standards (Table 2.4). At the federal level shallow geothermal energy is covered by mining and water laws (MVV 2007, Ground Reach 2008). Geothermal heat energy is considered a federal asset in Germany. However if it is used on-site or is shallower than 100 m it is not governed under mining law which has led to increasing number of 99 m boreholes (Banks 2008). Therefore shallow geothermal systems are mostly governed by the water law (Ground Reach 2008). German standards and design guidelines are among the most developed ones in the world. The *VDI 4640* regulation – thermal use of the underground – initiated at late 90's (Reuss et al. 2006) comes in 4 parts: Part 1: General, Licenses and Environment, Part 2: Ground Source Heat Pumps, Part 3: UTES, Part 4: Direct uses (cooling, air heat exchanger). The regulations are available in both German and English; nevertheless, only the German version is authoritative. The standard covers a wide variety of issues including suggested heat extraction rate for different geological conditions, formulations and graphs to calculate the system size, grouting and refrigerant types, in order to facilitate proper designing.

2.4.7 Netherlands

Netherlands geothermal energy production is mainly through GHPs (Lund and Bertani 2010). The use of GHPs and ATES systems in Netherlands dates back to the 1980's (Snijders 2005). Early systems were mainly open loop but since the 1990's closed loop systems gained more popularity and 10,000 of such systems were in use by beginning of 2010; the market is established and in a developing phase (van Heekeren and Koenders 2010). Due to its sedimentary geology, the Netherlands is suitable for ATES and has become a pioneer in system design and development; even with modest governmental support the penetration and growth rates are enormous (van Heekeren and Koenders 2010). By 2004 approximately 200 ATES systems were operational (Andersson 2007). Alternatively reported by IFTech International B.V., over 400 ATES projects applying either cold storage or a combination on cold and heat storage UTES were operational in Netherlands (Snijders 2005).

Open loop systems need a groundwater permit if the pumping rate is higher than 10 m^3/h; smaller systems and closed loops are exempt (Ground Reach 2008). With the great popularity of heat utilization from groundwater concerns have risen regarding the need for comprehensible regulations to prevent possible interferences, even though they currently exist in some local authorities (van Heekeren and Koenders 2010). New regulations for closed loop systems were to put into practice under which acquiring a permit will be compulsory (Haehnlein et al. 2010).

2.4.8 Norway

Since Norway reached its limit on utilizing hydropower as a renewable energy source in 2005, low temperature geothermal energy is gaining more interest (Haehnlein et al. 2010). 15,000 GSHP are reported to be installed in total most of which are water-filled vertical loops with no grouting under the typical Scandinavian approach (Midttømme 2005, 2008). There are approximately 100 large commercial systems, for example, Oslo Airport ATES (Midttømme 2005); Nydalen with 180×200 m wells in hard rock (Curtis et al. 2005, EGEC 2008) and Nye Ahus, Lørenskog with 350×200 m deep boreholes (70 km boring) (EGEC 2008) being some of the largest BTESs in Europe. The scheme “Heat Pump Ordinance” (Varmepumpeanordningen) was initiated in 2000 by NVE (Norwegian Water Resources and Energy Directorate) and industry organizations. It is run by NOVAP (Norwegian Heat Pump Association) which provides training and accreditation for installers, and sets standards for installation and service (Markusson et al. 2009).

2.4.9 Sweden

Sweden tops the European GHP sector in the number of heat pump installations (>300,000 GSHP) (Toneby 2010) and per capita use (35 per 1000 capita) (EGEC 2008). Sweden's installed total heat pump capacity is the second in the world. Sweden is also one of the leading countries using UTES technology. As of 2007, 38 ATES systems are reported to be operating in Sweden (Andersson 2007). The success of ground source energy utilization in Sweden is perhaps due to lenient regulations (Ground Reach 2008), and less costly installation in Swedish crystalline hard rock geology (usually minimal need for casing and/or grouting). Because of the thin soil cover, limited groundwater resources, and risk of salinization in coastal regions, most of the systems are vertical closed loops. Around 30% of over 310,000 well records in the Geological Survey of Sweden (SGU) database are energy wells (Törnros 2007, Dehkordi 2009).

Swedish *Normbrunn -07*, "*Standard Procedure in the Implementation of Water and Energy Wells*", covering both water wells and energy wells, has a focus on protecting groundwater quality. It is primarily aimed at well drillers as a training and awareness tool but does impose certain guidelines which are followed up on by municipalities. In order to reduce the risk of decreased system efficiency, and possible borehole icing and a subsequent refrigerant leak, the standard recommends boreholes be placed in the center of property, angled drilled away from adjacent systems, or increasing borehole depth. Grouting of energy wells is addressed both in terms of energy efficiency (it can reduce the heat exchange by 25-30%) and protecting aquifers. Due to risk of encroaching salinity along the Swedish coastlines, the bottom saltwater portion (chloride content > 50 mg/l or conductivity > 50 mS/m) and part of the freshwater depth is recommended to be grouted. In addition, the top portion of borehole is always required to be cased at least 6 m from the surface and sealed 2 m into the rock interface. If sedimentary rocks are encountered, complete sealing must be used to prevent shortcutting between aquifers. For major groundwater resources extensive studies are required. Supplementary regulations can be imposed at a community (Kommun) level. The Swedish Geotechnical Institute (SGI) has also published state of the art reports such as *SGI-Varia 511* (Systems for heating and cooling of the land – A baseline description) by Rosén et al. (2001) and *SGI Varia 556*

(Systems for heating and cooling of the land – Demonstration object of geothermal plants) by Rosén et al. (2006).

2.4.10 Switzerland

Switzerland has the highest number of GHPs per unit area in Europe (1.3 per km^2) (EGEC 2008), and an annual growth rate of 15% in GHPs (Curtis et al. 2005). GHPs form the main part of Swiss geothermal energy production (Lund and Bertani 2010). According to Curtis et al. (2005), 65% of the GHP systems are vertical closed loops, 30% open and 5% horizontal loops. Using double U-tubes is the common approach in Switzerland (AWP T1 2007) which decreases the required borehole depth. AWP (Heat Pump Working Group, Zurich) guidelines, in 12 parts, are the related Swiss standards covering different aspects of geothermal heat pump systems; *AWP T-1, 2, 3* are more related to the scope of this study. By means of basic formulations, graphs and tables the AWP regulations provide helpful instructions on correct designing of an individual open, vertical, horizontal and pond system.

2.4.11 UK

Despite the global increasing popularity of shallow geothermal systems, especially, closed loops, they have not been widely recognized in the UK until recently. While open loop systems are more often used, the penetration rate of systems in general is very low in the UK compared to other developed countries (Banks 2008). While regulations exist for open systems (permits required for systems > 20 m^3/day) only some general guidelines are given for closed loop systems. The closest legislation is perhaps the groundwater protection policy by the British Environment Agency which mostly applies to open systems. The basic guide "*Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems (– A guide for specifiers, their advisors and potential users)*" (Energy Efficiency Best Practice in Housing 2004, Energy Saving Trust 2007), was prepared on behalf of the government to increase awareness. Overall, the statements and legislations on closed loop systems are very general and undeveloped in comparison with some other European states. For installing closed loop ground source systems, a permit is not generally required; however the environmental agency may advise measures to minimize the risk of hydraulic connection between aquifers, temperature changes and leakage.

2.4.12 USA

The USA utilizes geothermal energy mainly through GHPs and has the world's largest GHP capacity, but systems are typically overdesigned with fewer full load hours relative to countries like Sweden and Norway (Lund et al. 2004, Lund and Bertani 2010). A study in 1998 showed around half of the states had no specific regulations on closed loop GSHP systems (Den Braven 1998, Banks 2008). However by 2010, 82.4% and 36.4% of the states have regulated vertical and horizontal closed loops respectively; while nearly all the states regulated open loops (National Ground Water Association 2010a). A study performed by the National Ground Water Association (NGWA) indicates that nearly 95% of open loops, 90% of standing columns (open loop with extraction and disposal in the same well but in different depths), 80% of vertical closed loops are currently regulated in 34 states (National Ground Water Association 2010a). NGWA (2010b) has compiled the "*Guidelines for the Construction of Loop Wells for Vertical Closed Loop Ground Source Heat Pump Systems*", a non-enforced guide, from "external reliable sources". In addition the *American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) handbook* dedicates a chapter to "*Geothermal Energy*" which includes geothermal heat pumps (2007). It provides instruction on heat load, system design and layout of open and closed loops, and standing columns; some of which are collected from other sources. The *ASHRAE handbook* also includes guidance on installation, grouting and antifreeze.

According to Banks (2008) *New Jersey* has perhaps the most regulated conditions in the USA. There are also technical guides available for the *City of New York* (Collins et al. 2002) and *Washington* (Lyons 2009). A noteworthy example at the state level is *Missouri* where, similar to the Scandinavian approach, only the bottom 30 ft. of bedrock wells need to be grouted whereas in *Massachusetts*, and *NGWA guidelines*, grouting the entire GHP is suggested. In addition open and closed loops in *Massachusetts* with a flow greater than 15,000 gpd requires a permit. In general the dominant approach in US states appears to be setting distance boundaries rather than temperature limitations. See Tables 2.3 and 2.4 for more details.

2.4.13 Others

One main goal of this study was to investigate the notable GHP regulations and conduct a detailed review on them. Other countries, in general, lack appropriate guidelines to aid in the design of efficient GHP systems and regulations that protect the environment from GHP systems. At one extreme, there are countries like Greece and Italy, with modest utilization and legislation of ground source heat, which benefit from European level regulations. For instance in Greece, subsurface heat below 25 °C is defined as private, utilizable by the land owner, but a permit must be granted to install and use a GHP system after being studied by a competent professional. Italian geothermal production is regulated at the industrial level (Ground Reach 2008), and while there are some regulations applied in local level (e.g. in Lombardy), legislations are often unclear (Banks 2008). Lack of policy, regulation, economic incentives and knowledge can further hinder penetration of the technology in Italy (Cappetti et al. 2000). At the other end, most countries have a limited share of their energy supplied by GHPs and have inadequate regulations on this matter.

2.5 Discussion and Conclusions

This study shows that open loops are most frequently regulated, usually under groundwater acts or environmental laws. This is because they are in direct interaction with groundwater and extract large amounts of water which may cause more immediately apparent environmental problems if not properly designed and operated. Erroneously, as closed loop systems do not extract groundwater the environmental impacts are usually smaller and negative system performance issues take more time to become apparent, they are not regulated to the same extent. Currently some GHP systems are exempted from regulations, or are more easily granted permits. This can lead to less efficient (i.e. high density of shallow BHEs) or higher risk installations (i.e. deeper BHEs that penetrate aquitards).

While limitation on minimum, maximum and differential temperatures is an important measure to ensure thermal sustainability and reduced environmental impact, it is less commonly addressed in the standards as well as the research literature. Even countries such as Sweden and the US, which have relatively comprehensive GHP regulations, lack temperature guidelines. Austria, Denmark, Germany and Switzerland are the few countries that have regulations in place for such considerations. In this context there have been concerns about the conflict of groundwater use as an energy source and water resource, e.g. in France and Netherlands. Imposing temperature thresholds is an effective measure to preserve the quality of groundwater as a water resource.

Regarding minimum distance criteria, some of the suggested limitations (e.g. to roads, buildings, other properties), appear to be arbitrarily chosen. Others such as the distance from property lines, as imposed by countries such as Finland and Sweden, are very relevant as they can reduce potential system interference. Denmark and Sweden have the greatest distance requirements between GHP systems. Higher thresholds in the Nordic countries may be linked to the longer operating hours (or heat transport in fractures in case of Sweden) which is a good example of accounting for local conditions. Otherwise, regulated distances between BHEs often appear to have their basis from the research literature which normally excludes heat transport due to groundwater advection (Table 2.4). It is also clear from our review of the design software that the effect of groundwater flow has been largely neglected which is not a proper assumption under advection dominated transport and leads to non-optimal design. Although some regulations propose hydrogeological investigations and groundwater modelling, they do not propose minimum thermal differentials that will allow for the setting of distance thresholds which may be more relevant for larger systems. In any case, the thermal plume from one system can affect downgradient system(s). Some standards require or recommend coupled BHE and groundwater modelling on a case by case basis, especially for larger projects. However, overall it appears that many of current design procedures and regulations are falling behind the current state of research.

Proposing allowable specific heat extraction rates, as done in Germany and Switzerland, is a good practice in combination with distance and temperature thresholds which can be directly applied in the design process. Furthermore, the inherent variability in geologic material, including porosity, hydraulic conductivity, and thermal conductivity, are not widely recognized in the regulations. Germany and Switzerland recommend lower heat extraction rates in material with low water content and poorer thermal conductivities; Sweden recommends different distance criteria in soil versus rock. An appropriate measure to integrate the groundwater effect on system performance is application of TRT and apparent thermal conductivity. However, this will not accurately account for the potential impact on nearby systems, unless the flow rate and direction are known. With multi borehole systems knowledge of heating/cooling or recovery periods is also required.

Considering the growth rate of GHP systems and the current status of guidelines and legislations, the necessity for improved and dedicated standards to ensure that installations are sustainable is essential. There is a similar need for improvement in the design methods, which can be integrated in the guidelines, by clearly imposing the requirements for including the advective heat transport in the models under certain hydrogeological conditions. For example, research has shown that advective heat transport is important in hydraulically conductive geological material and under high gradients, where the groundwater flux exceeds 10^{-8}–10^{-7} m/s. Only a small number of governing authorities have introduced some sort of applicable guidelines. Even in such cases, standards from different disciplines may apply and these may not explicitly cover GHP systems as the field is very interdisciplinary. The approach taken by countries such as Denmark, Germany and Switzerland, having dedicated guidelines for GHP systems, is likely the most appropriate since it makes the process simpler and reduces ambiguity. Contrast this with Belgium where the major restriction is a drilling permit; or the initial situation in Ontario (Canada) where it was felt that the existing provincial ‘wells’ legislation would indirectly cover GHPs. However, in Ontario problems arose with the installation of closed loop GHPs and separate legislation was implemented in an attempt to better regulate. Due to the benefits of the Scandinavian approach in not grouting the BHEs, this approach could be considered in parts of the Canadian Shield which have a similar geology. Use of safer antifreeze and casing/sealing the top portion of the BHE minimizes the risk concerns. The approach taken by the legislators in Canada is similar to other federal countries, like Germany and US, with federal and state levels of regulations in place. However, the Canadian *CSA C448-02* lacks the qualities of the *VDI 4640* and the *ASHRAE Handbook* in terms of providing clear measures to guarantee sustainable thermal design and performance. Some Canadian provincial regulations are rather recent and not fully developed yet. Current legislations are scattered, general and vague in most cases, thus hindering the development of the geothermal industry in Canada. A framework in which a basic federal guideline is dedicated to geothermal heat pump systems, referring to all other related legislations at the federal and provincial levels, would facilitate the process. As the Canadian GeoExchange Coalition (CGC) already plays a nationwide role in providing quality assurance to the consumer by geothermal system certification, and the training and accreditation of the geothermal professional, it is the logical choice as the lead authority for updating and legally enforcing *CSA C448-02*. The CGC could also act as a channel for publicly publishing relevant provincial regulations and for facilitating better interaction between the federal government, provincial authorities and the public.

While it is likely that the minimal harmonization between standards in various jurisdictions results from significant differences in geography, geology, climate, energy use and socio-economic aspects, generic design guidelines that account for such differences should be possible for smaller systems. Increasing the homogeneity in the criteria through synthesizing them is a recommended pathway to better guidelines. Larger systems with higher energy demand and more number of boreholes may require fully integrated hydrogeological numerical modelling studies coupled with building heating, ventilation, air conditioning (HVAC) design. This suggests the need for integration between professionals with expertise in ground conditions (e.g. hydrogeologists, geotechnical engineers) and HVAC design experts (mechanical engineers). It also suggests the need for integrated regulations both between professions and levels of government. As discussed previously some jurisdictions rely on resource or environmental based regulations for BHE installation while relying on locally enforced building code regulations that attempt to guide BHE design – inside and outside the building envelop. This approach only serves to deter integration between professions which can lead to errors in system design, sustainability, and environmental impact.

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Chapter 3

3 Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems

3.1 Introduction

Ground-source heat energy is a globally utilizable renewable source of energy. It is driven by the nearly constant ground temperatures below ca. 10 m depth which can be used to extract heat in winters and serves as a heat sink in summers. Ground-source energy is usually used in conjunction with geothermal heat pumps (GHPs) to bring the temperatures to the desired level for heating/cooling. The emerging popularity of GHP technology has resulted in a call for improved design methods and regulatory measures.

Thermo-geological factors are more frequently studied in the research literature and reflected in design and regulations. Here, thermo-geological factors mean those that exclusively are related to heat transport and have no influence on groundwater flow, e.g. thermal properties of soil particles. Although computer codes able to model coupled groundwater flow and heat transport exist, and there are some regulations in place which consider thermo-hydrological factors in a superficial manner, the great majority of the design methods and software do not account for the heat transport by groundwater advection. Thermo-hydrological factors are those that impact the groundwater flow and the heat transport, e.g. hydraulic gradient.

According to Eskilson (1987) the vertical average undisturbed ground temperature (i.e. background temperature) is sufficient for modelling borehole heat exchangers (BHEs), and the surface seasonal variations, as well as geothermal gradient, can be neglected. Kurevija et al. (2011) found that this is valid when geothermal gradients are relatively low, i.e. 1.62 °C/100 m, but can become important at higher gradients, i.e. 5 °C/100 m. The background temperature can be measured by circulating the heat carrier fluid in the borehole, without an external heat source/sink, through a thermal response test. The regional ground temperatures often are known fairly accurately from previously acquired data; however the ground temperatures may significantly change in time due to urbanization (Ferguson and Woodbury 2007) or by adjacent geothermal systems (Ferguson and Woodbury 2006). Thus, updating background temperature data for designing new installations and quantifying the impact of such change on performance of previously installed BHEs may be appropriate. Loop temperatures also are linked to the thermal performance of the BHE as well as to the magnitude of its subsurface temperature disturbance; however, in contrast to the background temperatures they are controlled by the system. Thus, according to the review by Haehnlein et al. (2010) some geothermal guidelines, i.e. Austria, Germany and Denmark, set limits on loop temperatures. In this context, it is important to assess the effect of loop temperatures and heat extraction rate on subsurface thermal impact and temperature reversion.

One of the most important properties of the grouting material that affects the borehole thermal resistance is its thermal conductivity (Zeng et al. 2003). Hellström (1998) shows that grout material with poor thermal conductivity significantly increases the borehole thermal resistance; however, its extent is sensitive to the spacing between the pipes (Hellström 1998; Wagner et al. 2012; Witte 2012). Although these studies are related in their use of thermally enhanced grout to lower borehole thermal resistance, the degree to which thermally enhanced grout can improve long-term BHE performance remains unknown.

While the design and thermal sustainability of BHEs has been studied for many years (e.g. Ingersoll and Plass 1948; Ingersoll et al. 1950; Andrews 1978 amongst the earliest), today the literature is dominated by studies where groundwater flow is not considered or presumed to be of negligible importance. Even in the international standards, like the German VDI 4640 standard (VDI 2001) and the Swiss AWP-T1 (AWP 2007), thermal conductivity and borehole specific heat extraction are related through the underground material and its water content (but not its movement). Rybach and Eugster (2002) evaluated the sustainability of a single BHE; and Signorelli et al. (2005) extended this work to multiple BHEs so as to determine the borehole spacing at which there is no thermal interaction. Signorelli et al. (2005) determined that, for a single

BHE, the time required for thermal recovery, i.e. the return of ground temperatures to their initial temperature after shutting down a system, is equal to the operation time. Later Priarone et al. (2009) studied performance of single and multiple BHEs both without and with complete seasonal thermal recharge, i.e. completely balanced and unbalanced heat load functions. They concluded 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.

Recently, there has been an interest on evaluating the effect of groundwater flow on BHEs. A preliminary assessment of the effect of groundwater flow by Chiasson et al. (2000) shows the Péclet number is a relevant indicator but also mentions that its exact value depends on the choice of characteristic length. According to their simulations, heat transport by groundwater flow can be significant in high hydraulic conductivity materials. They also estimate the effective thermal conductivities and conclude that higher groundwater velocity increases effective ground thermal conductivity. Gehlin (2002) concludes that groundwater flow (in continuum, porous zone or fracture form) significantly changes temperature in and around a borehole. Their results show approximately 5 °C and 2 °C change in loop temperatures under groundwater velocities of 10^{-6} m/s and 10^{-7} m/s respectively. These changes would approximately equal a ten and two fold increase in effective thermal conductivity. Computations by Diao et al. (2004) show that groundwater advection in the porous medium may alter the temperature distribution compared to a conductive dominated regime, leading to lower temperature disturbances and an eventual steady-state condition around the BHE. They derive an analytical solution for a line heat source in an infinite medium – comparable to Kelvin's line source model – which accounts for groundwater advection. Péclet numbers higher than 0.1 are reported to enhance the heat extraction rate (Fuji et al. 2005). Furthermore, the influence of groundwater flow on thermal response test (TRT) results was observed by Lee and Lam (2009), who could rather confidently estimate the groundwater velocities over 2×10^{-7} m/s. A sensitivity analysis on thermally affected zones (TAZ) around open geothermal loops by Lo Russo et al. (2012) verifies that hydraulic conductivity and gradient, and porosity, are highly important in those systems. This was one of the few studies that examined the effect of porosity on GHPs – but in an open loop. Open loops function similar to closed loops but extract the heat through direct withdrawal of groundwater and not through a heat exchanger; therefore advective heat transport due to groundwater flow plays a more important role in open-loop systems. In some studies on closed loops, the porosity is either changed with hydraulic conductivity or is kept constant and the velocity varies strictly through varying the hydraulic gradient and hydraulic conductivity (e.g. Chiasson et al. 2000; Wagner et al. 2012). A sensitivity analysis on artificial heat injection – not natural groundwater flow – by Vandenbohede et al. (2011) has found the process most sensitive to thermal conductivity of the solid, porosity, heat capacity of the solid and the longitudinal dispersivity, in that order.

The effect of the variability in subsurface flow and transport properties, which if not explicitly included in a model is represented by dispersivity, has not been well addressed and remains controversial despite its potentially important effects on heat distribution in the subsurface (Ferguson 2007; Hidalgo et al. 2009). In heat transport, heterogeneity in thermal properties and perhaps hydrodynamic thermal dispersion are the related factors. In regards to the relationship of thermal dispersivity with groundwater flow, Ferguson (2007) and Hidalgo et al. (2009) confirmed this connection, while, on the contrary Doughty et al. (1982) considered it to be otherwise. Sauty et al. (1982) suggests including the hydrodynamic dispersion and correlation between the effective thermal conductivity and Darcy velocity. With this assumption, a thermal response test sensitivity study by Wagner et al. (2012) indicates that thermal dispersivity of the subsurface can affect the effective thermal conductivity measured in the test; although they assumed a rather high Darcy velocity of 0.1 m/day (i.e. 1.15×10^{-6} m/s).

Groundwater flow can help to reduce the BHE installation length and cost through increasing the effective thermal conductivity of the ground and enhancing the heat exchange process (Wang et al. 2012). Therefore including groundwater flow in the design procedure can increase the economic sustainability of the system. According to Diersch et al. (2011b), in thermal storage systems, groundwater may have a rather significant impact on the system thermal performance and long-term efficiency by transporting the stored heat away from the BHEs. Given that the large majority of BHE systems are currently designed based on a heating/cooling load balance (i.e. no groundwater flow), in reality, the loop will not function as designed.

In order to have efficient and practical designs and guidelines – which effectively integrate groundwater flow – major parameters and thermo-hydrogeological factors influencing the system performance as well as its impact have to be determined. This study includes assessment of thermal plume growth and dispersion. Sensitivity analysis on major hydrogeological, system and meteorological factors (groundwater flux, subsurface thermal conductivity, volumetric heat capacity, thermal dispersivity and porosity, grout thermal conductivity, background and loop inlet temperatures) is performed to identify the key factors. Borehole depth and loop flow rate are not included as they are the dependant designed aspects and will affect the installation and operation costs. The aim is to classify the main parameters affecting thermal efficiency of BHEs. The results will also provide a basic approximation of how much the efficiency of a single BHE may change under different conditions. While some of the parameters studied have been evaluated by other authors, the approach in this paper – simulating all the parameters in one model over a system life time – allows for a sounder classification and comparison between them. Groundwater flow and geology can also affect the thermal recovery – reversion of temperatures back to initial state – at the borehole, and surroundings after system abandonment. This is important as environmental and thermal sustainability issues can extend beyond a system's lifetime. Examples of such issues are concerns with quality of drinking-water resources and thermal performance of future installations (Oriol 2010). Thermal recovery is also relevant in the short-term when a system's thermal load includes a season with no net heating/cooling load. Thus, in addition to the operation phase, recovery of temperatures under different conditions is also studied. Although for simplicity, this study is done for a single borehole and the key findings can be extended to multi-borehole arrays.

3.2 Model setup and scenarios

Modelling is performed in FEFLOW® which is a density-dependant fully coupled groundwater flow and heat transport code (DHI-WASY 2013). In FEFLOW®, modelling of the vertical closed loop is possible under two different approaches (Diersch et al. 2010, 2011a, 2011b): 1) discretizing all borehole elements and assigning flow and thermal material properties on a nodal/element basis in, what is referred to as, a fully discretized three-dimensional model (FD3DM) – selected for this study; and 2) a built-in module where a simplified one-dimensional (1D) element (BHE solutions) is inserted at the center node of the BHE and coupled with the rest of the model domain (Figure 3.1). The discretized approach increases the computation time and amount of resources needed but output of the detailed temperature distributions, within and near the borehole, is a key benefit of this method. This makes it especially suitable when analyzing the design features of a single borehole. As only one BHE is modelled here, accurate results can be achieved using a reasonable amount of computational resources.

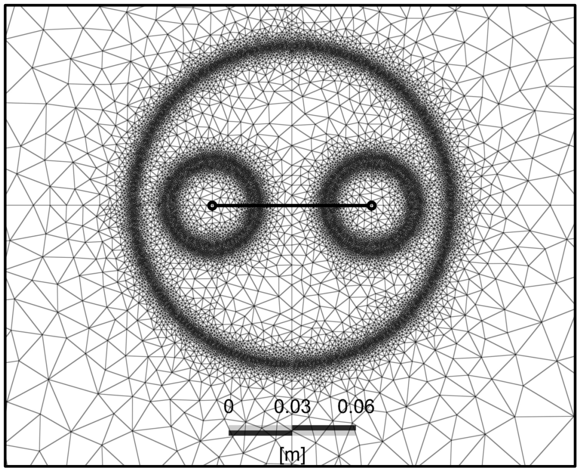

Figure 3.1 Discretized BHE finite element mesh and the linear DFEs in the bottom slice. Vertical elements are denoted by the circles in pipe centers and the horizontal element is symbolized by the connecting line.

3.2.1 Base scenario

The discretized finite-element model is comprised of the fluid inside the pipe, pipe wall, grout and the surrounding soil-groundwater matrix. The horizontal model domain is 100 m×100 m. The element size varies from about 2 m at the borders down to 0.5 mm at the pipe and borehole walls. Discretization in vertical direction is done by inserting slices every 1 m in depth. The modelled BHE depth is 100 m, forming 101 slices. The flow inside the tubes is represented by 1D discrete feature elements (DFE) passing through the center of the pipes and connecting in the bottom in a U shape (Figure 3.1). The loop flow rate and inlet temperature are assigned at the DFE location in the top slice as boundary conditions. In order to represent the almost instantaneous transverse heat transfer inside the tube due to the turbulent flow regime (to maximize the heat exchange through the pipe walls), relatively extreme values are assigned to thermal properties inside the tube (i.e. heat conductivity 1000 J/m/s/K and specific heat capacity 0.001 MJ/m^3/K) with an anisotropy factor of zero – to prevent vertical interference. This results in high thermal conductivities in the x and y directions and zero in z direction (depth) inside the tube. The heat extraction is defined by a constant loop inlet temperature of 0 °C; the subsurface initial and background temperature is 10 °C. These are both representative values as they are in agreement with the common practice and literature (Banks 2008, 2012; VDI 2001). Total simulation time of the model is 25 years. The borehole settings and material properties are presented in Table 3.1. The assigned hydrogeological properties are the base values from Table 3.2 (Domenico and Schwartz 1998; Hellström 1991).

Table 3.1 In-borehole setting and material properties for the base scenario.

Parameter	**Unit**	**Value**
Dynamic Viscosity of Refrigerant	10^{-3} kg/m/s	2.75
Thermal Conductivity of Refrigerant	J/m/s/K	0.415
Heat Capacity of Refrigerant	10^{+3} J/kg/K	3.873
Density of Refrigerant	10^{+3} kg/m^3	1.045
Flow Discharge of Refrigerant	m^3/d	25
Thermal Conductivity of Grout	J/m/s/K	2
Volumetric Heat Capacity of Grout	10^{+6} J/m^3/K	1.5
Borehole Diameter	m	0.1524
Pipe Distance (center to center)	m	0.075
Pipe Outer Diameter	m	0.0381
Pipe Wall Thickness	m	0.0035
Thermal Conductivity of Pipe	J/m/s/K	0.45
Depth	m	100
Background temperature	°C	10
Inlet Temperature	°C	0

Table 3.2 Parameters examined in sensitivity analysis and their base scenario values as well as upper/lower limits. Flux values in parentheses are products of hydraulic conductivities and gradients. Only one parameter is varied at a time.

Parameter	**Unit**	**Lower Limit**	**Base Value**	**Upper Limit**
Hydraulic Conductivity	m/s	10^{-10}	10^{-6}	10^{-3}
Hydraulic Gradient	-	0	0.001	0.1
Darcy flux	m/s	0 (and 10^{-13})	10^{-9}	10^{-6} (and 10^{-7}, 10^{-8})
Thermal Conductivity of Solids	J/m/s/K	1.5	3	4.5
Volumetric Heat Capacity of Solids	10^6 J/m^3/K	1.5	2.5	3.5
Porosity	-	0.05	0.3	0.5
Longitudinal Thermal Dispersivity	m	0.1	0.5	1
Transverse Thermal Dispersivity	m	0.01	0.05	0.1
Thermal Conductivity of Grout	J/m/s/K	1	2	3
Background temperature	°C	7.5	10	12.5
Inlet Temperature	°C	-5	0	5

3.2.2 Sensitivity analysis scenarios and fundamentals

In this study, the sensitivity analysis is done following the one-factor-at-a-time method; all material properties and boundary conditions are maintained constant at all times, except the parameter on which sensitivity analysis is performed. Each variable is changed independently from the others. This approach allows maintaining full control over the model inputs and simple analysis of the outputs.

The three-dimensional (3D) governing equation of heat transport in two phases (solid-fluid) can be re-written as Equation 3.1 (after Anderson 2005; Chiasson et al. 2000; Domenico and Schwartz 1998; Saar 2011):

$$\frac{\partial T}{\partial t}+\frac{\rho_f\cdot c_f}{\rho\cdot c}\nabla.(T\,\mathbf{q})-\frac{\lambda\,\mathbf{I}+\left(\alpha_T\cdot|\,\mathbf{q}\,|+(\alpha_L-\alpha_T)\frac{\mathbf{q}\otimes\mathbf{q}}{|\,\mathbf{q}\,|}\right)}{\rho\cdot c}\nabla^2 T=Q_H \qquad (3.1)$$

where:

$$\rho c = \varepsilon_f \rho_f c_f + \varepsilon_s \rho_s c_s \tag{3.2}$$

$$\lambda = \varepsilon_f \lambda_f + \varepsilon_s \lambda_s \tag{3.3}$$

are the bulk volumetric heat capacity and bulk thermal conductivity, respectively (see Table 3.3 for notations). According to Equation 3.1, the groundwater flux (*q*), the product of hydraulic conductivity (*K*) and hydraulic gradient (*i*) defines the rate of heat transported by advection. In reality where porosity (ε_f) and K are constant material properties, as the Darcy velocity (*q*) is also equal to the product of porosity and groundwater pore velocity (*v*), increase in gradient is seen as increase in velocity and affects the advective transport through altering the pore velocity. Changes in porosity, under constant groundwater flux of the base scenario in this study, will lead to corresponding variation in velocity and thus unchanged heat transport by advection. It should be noted that this is valid under the assumption of porosity and hydraulic conductivity being varied independently. In general, porosity does not play a role in advective heat transport when comparing cases with the same groundwater fluxes. Porosity (ε_f) controls the conductive portion of the heat transport through bulk thermal conductivity and volumetric heat capacity (Equations 3.2 and 3.3).

The dimensionless thermal Péclet number, as formulated by Domenico and Schwartz (1998), is expressed in Equation 3.4. It is the ratio of advective heat transport by bulk fluid motion to conductive heat transport by the solid-fluid matrix, i.e. bulk thermal conductivity (Equation 3.3).

$$Pe = \frac{\rho_f c_f q L}{\lambda} \tag{3.4}$$

where *L* is characteristic length.

Table 3.3 Notations used in the formulations.

Symbol	Parameter	Unit
Standard parameter notation		
c	Specific heat capacity	J/kg/K
H	Heat energy	J
h	Hydraulic head	m
I	Identity matrix	-
i	Hydraulic gradient	-
K	Hydraulic conductivity	m/s
L	Characteristic length (in Equation 3.4)	m
L	Borehole length (in Equation 3.8)	m
P	Power	J/s or W
q	Darcy flux	m/s
Q	Flow	m^3/s
S	Specific heat extraction rate	J/s/m or W/m
t	Time	s
T	Temperature	K or °C
v	Velocity	m/s
α	Thermal diffusivity	m^2/s
α	Thermal dispersivity (if with subscript)	m
ε	Portion of volume in each phase, i.e. ε_f= porosity	-
λ	Thermal conductivity	J/m/s/K
ρ	Density	kg/m^3
Subscripts and superscripts		
f	Fluid	-
H	Heat	-
i	Inlet	-
L	Longitudinal	-
o	Outlet	-
r	Refrigerant	-
s	Solid	-
T	Transversal	-

In this study, thermal dispersivity values are assigned based on the scale of the problem domain, assumed to be in the same order of solute dispersivity and have a $\alpha_L/\alpha_T=10$ ratio. Also here thermal dispersion is linked to the groundwater flux; therefore longitudinal and transverse thermal dispersion become more important in the heat transport equation (Equation 3.1) under higher groundwater flows.

Thermal diffusivity (α) is the ratio function of thermal conductivity on volumetric heat capacity (see Table 3.3 for notations):

$$\alpha = \frac{\lambda}{\rho c} \tag{3.5}$$

In conduction-dominated heat transport, thermal diffusivity defines how quickly a material can come to thermal equilibrium and how efficiently heat is conducted through it. Therefore, increase in thermal conductivity and volumetric heat capacity will respectively improve and deteriorate the heat conduction. Volumetric and specific heat capacity of soils and rocks commonly are considered to be constant or otherwise varying in a narrow range. Consequently it is the thermal conductivity that controls the thermal diffusivity of the subsurface. In Equation 3.1, heat conductivity and heat capacity appear in different components of the equation and will be studied individually here.

While heat load function can be analysed as a separate factor, it is especially influential regarding sustainability of multi-borehole systems. As a single BHE is modeled here, to make the analysis more straightforward and to exclude other sources of variation in the results, the thermal load has been simplified to a constant inlet temperature rather than seasonal cyclic. Nonetheless, in most cases the heat load will not be completely balanced which leads to accumulation of the off-balance in the long-term; therefore, the constant heat extraction – without seasonal thermal recharge – will be the worst-case scenario.

A summary of analysed variables and their range is presented in Table 3.2. While a wider range might be possible for some of the factors, the sensitivity analysis focuses on the system response to parameter variations in their typical ranges (Domenico and

Schwartz 1998; Hellström 1991) and aims at highlighting the influence of each variable in its range and, also, relative to other parameters.

The outlet temperature of the loop is considered as the dependent analyzed variable since it is directly related to the thermal efficiency of geothermal systems. In each scenario, the specific heat extraction rate is calculated from the outlet temperature graph. The assessment is done at 6 months, comparable to one heating/cooling season in cyclic thermal load functions, and 25 years, representing the long term conditions. Loop outlet temperatures are related to heat extraction through the following equations:

$$\text{Total energy extracted} = H = \frac{\sum (T_o - T_i) \cdot \rho_r c_r \cdot Q_r \cdot \Delta t}{\sum \Delta t} \tag{3.6}$$

$$\text{Heat extraction rate} = P = {}^{H}\!/_{t} \tag{3.7}$$

where t, operation time, is assumed to be 8 hours/day.

$$\text{Specific heat extraction rate} = S = {}^{P}\!/_{L} \tag{3.8}$$

where L is the borehole depth.

3.2.3 Model validation and mesh convergence study

A mesh convergence study is the key to obtaining a satisfactory level of accuracy in a reasonable time. The sensitivity of results to mesh density is especially important in problems with high groundwater velocities and mesh Péclet numbers (Donea and Huerta 2003). Thus, here the mesh convergence study is done for the scenario with highest groundwater velocity (3×10^{-6} m/s). The mesh is refined until no change in outlet temperature and thermal plume size, the key relational parameters for this study, result from further refinement. With an additional step in refinement of the mesh – element size reduced to about half – no noticeable change in the plume extent and loop temperature (±0.01 °C accuracy) was observed.

To have further confidence in the accuracy of the results they are also validated against an analytical solution. For this purpose the method by Eskilson and Claesson (1988) is used, which is implemented in FEFLOW® and is chosen here due to its proven robustness and accuracy, especially when approaching steady-state conditions (Diersch et al. 2010), which is the case here as the inlet temperature is constant. The mesh convergence study has been done for the analytical solution as well; the mesh was refined except for nodes surrounding the BHE (see Diersch et al. 2010 for more details) multiple times to increase the accuracy under high velocities in this model. The agreement of the FD3DM and analytical results in Figure 3.2 – under no groundwater flow conditions – validates the model. Comparison between the analytical and FD3DM results under high velocity (i.e. 3×10^{-6} m/s) shows a slight difference; however the error is negligible (less than 5%). Since the two models are validated against each other under no groundwater flow, and as mentioned in the preceding section 'Model setup and scenarios', the FD3DM approach is generally considered to be more accurate and is accepted here as the reference solution. The performed FD3DM mesh convergence analysis under the case with highest groundwater velocity ensures accuracy and validity of the results under all of the modeled scenarios. For more in-depth comparison between modeling heat exchangers by analytical solution and FD3DM approaches in FEFLOW® see Diersch et al. 2010, 2011a, 2011b.

3.3 Results and discussion

From this point forward the term ‘plume’ is referring to the 9 °C contour line which corresponds to a 1 °C change from the initial subsurface temperature unless otherwise stated.

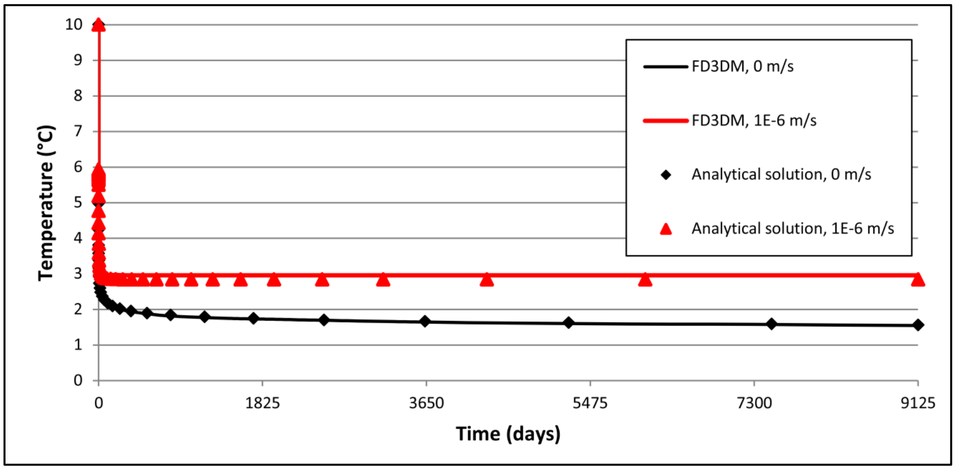

Figure 3.2 Loop outlet temperatures by the FD3DM model vs. the analytical solution under no groundwater flow and 10^{-6} m/s groundwater flux (3×10^{-6} m/s groundwater velocity).

The base scenario results show that temperature gradients in proximity of the BHE are higher and approach steady-state conditions quicker compared to those far from the borehole (Figures 3.3, 3.4a,b). Similarly, they dissipate more rapidly after the BHE shut down. Conversely, for the 9 °C isoline – far from the borehole – attenuation appears to begin after about 2 years, taking around 10 years to completely dissipate (Figure 3.3). Temperatures closer to the background initial temperature recover at a slower rate, while the extreme temperatures decline relatively quicker. This can be important depending on different thermal/environmental concerns. For instance, maximum subsurface temperature disturbance, which is addressed in some geothermal guidelines – e.g. VDI 4640 (VDI 2001) – is more spatially limited and reversible compared to subtle temperature changes that can affect aquatic ecosystems farther away (Markle and Schincariol 2007). The implications rise in multi-borehole and borehole thermal energy storage (BTES) systems where the size and temperatures are higher.

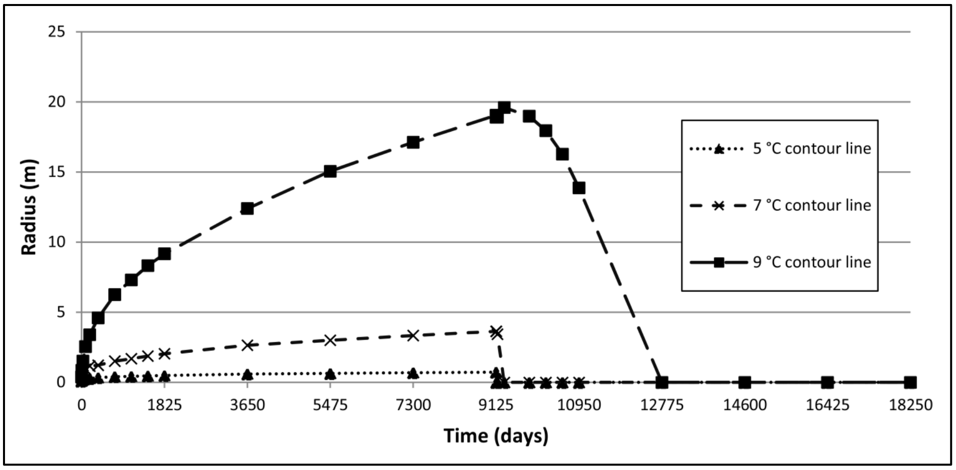

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Figure 3.3 Approximate radius of temperature isolines in production and abandonment phases at base-scenario conditions; groundwater flux 10^{-9} m/s, background temperature 10 °C.

Table 3.4 Summary of average borehole specific heat extraction rates in sensitivity analysis scenarios over 6 months and 25 years, assuming 8 h/day operation. See Table 3.2 for the ranges of the parameters.

Parameter	**Average Specific Heat Extraction rate (W/m)**					
	Lower Limit		**Base Value**		**Upper Limit**	
	6 months	**25 years**	**6 months**	**25 years**	**6 months**	**25 years**
Groundwater Flux	79	58.5	79	58.5	106.5	83.25
Thermal Conductivity of Solids	55.5	37.5	79	58.5	99	75
Volumetric Heat Capacity of Solids	79	58.5	79	58.5	79	58.5
Porosity	89.5	67.5	79	58.5	71	52.25
Thermal Dispersivity of Subsurface	79	58.5	79	58.5	79	58.5
Thermal Conductivity of Grout	73	54.5	79	58.5	82	60
Background temperature	60	45	79	58.5	104	72
Inlet Temperature	119	88	79	58.5	40	29.5

3.3.1 Groundwater flux

As mentioned in the preceding, groundwater flux, also known as Darcy velocity (q), is the hydrogeological parameter affecting the advective heat transport in the fluid-solid matrix. Increasing the Darcy velocity from 10^{-9} m/s to 10^{-7} m/s (Figures 3.4b,d), the 25-

year thermal plume becomes slightly longer (to 39 m from 36.5 m) and narrower (to 21 m from 36.5 m). However, the impact zone down-gradient spreads out a lot farther than it does up-gradient (34 m compared to 18.25 m); nevertheless, the plume, as already defined, decreases in area due to enhanced thermal dispersion and dilution by groundwater flow. Further increasing the velocity to 10^{-6} m/s makes the plume dramatically smaller (Figure 3.4f). Comparing the plumes at 1 year and 25 years under different groundwater fluxes 10^{-9} m/s, 10^{-7} m/s and 10^{-6} m/s shows that under higher groundwater flows, thermal plumes approach steady state considerably quicker (Figure 3.4).

Analysis of the outlet temperature versus multiple Darcy velocities (Figure 3.5) also shows that higher velocity results in higher heat exchange efficiency and a quicker BHE thermal equilibrium (i.e. approaching steady-state conditions). Under a velocity of 10^{-6} m/s, the equilibrium is reached in ca. 90 days, while with no groundwater flow, i.e. 0 m/s flux, equilibrium is still not completely achieved even after 25 years. The loop temperature gain (i.e. the difference between inlet and outlet temperatures) at 10^{-6} m/s is almost doubled compared to no flow conditions. In addition, calculated specific heat extractions in Table 3.4 show that under higher velocities the efficiency substantively heightens, which supports the hypothesis that hydrogeological factors may become central under certain conditions. In general, the results indicate that groundwater influence on loop temperatures starts to become significant at ca. 10^{-7} m/s and higher fluxes (Figure 3.5). However, the impact on the loop temperature is less significant than on the plume outline, which is because the borehole wall temperature dictates the BHE heat exchange at any time, not the far-field temperature. Figure 3.5 also indicates that the influence progressively escalates with every order of magnitude increase in groundwater flux. There is no appreciable difference among the low-range velocities. The common use of logarithmic scale for hydraulic conductivity and velocity may be misleading as they do not influence the heat transport logarithmically (Equation 3.1). Consequently, with every order of magnitude increase in velocity it will have increasingly more impact on system efficiency (Figure 3.5).

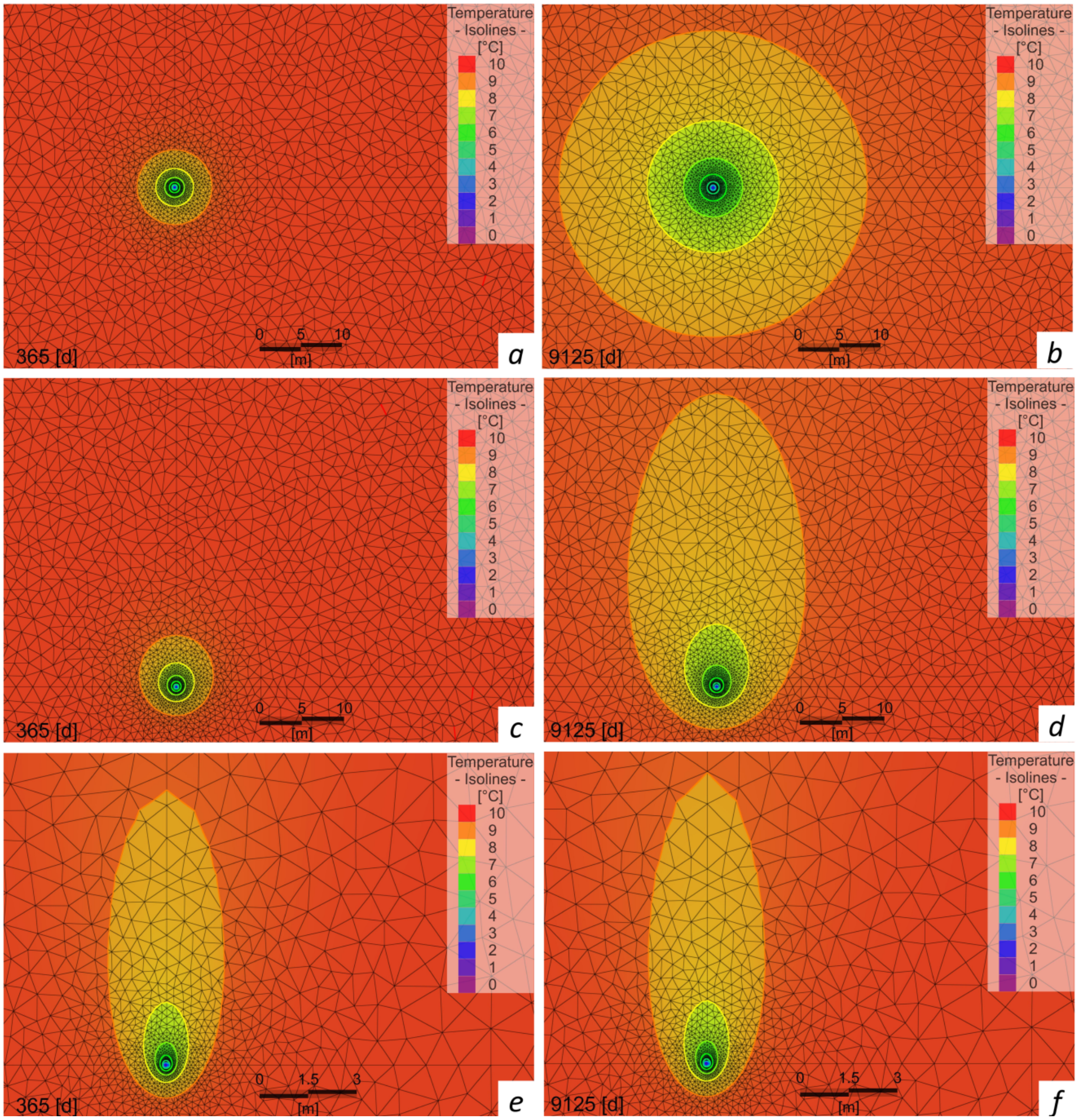

Figure 3.4 Thermal plumes under groundwater flux (a–b) 10^{-9} m/s, (c–d) 10^{-7} m/s, and (e–f) 10^{-6} m/s after 1 and 25 years. Note the scale difference. Flow direction is from bottom to top of all images.

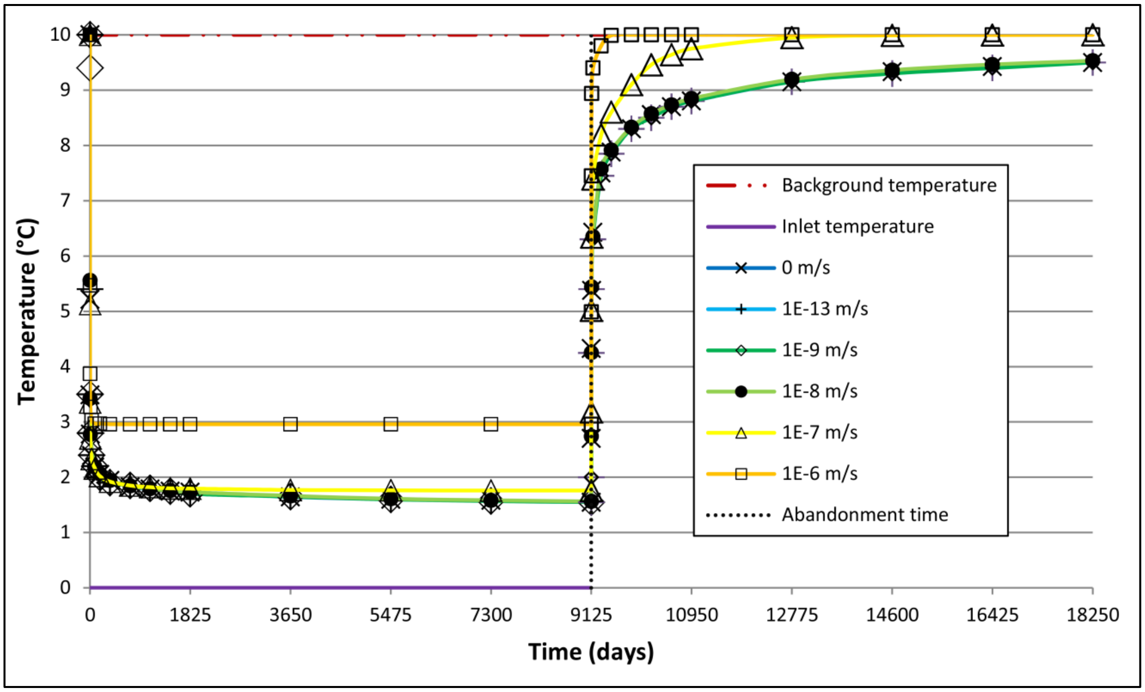

Figure 3.5 Loop outlet temperature vs. time under various groundwater fluxes during operation and after abandonment.

Similarly under the recovery period, groundwater flow drastically enhances the temperature to return to initial state (Figure 3.5). Groundwater flow appears to be more effective in thermal recovery as the conductive heat transfer by the BHE diminishes and advective component by groundwater dominates. As can be seen in Figure 3.5, at 10^{-8} m/s groundwater flux, impact on loop temperature is negligible during production but becomes noticeable during recovery period.

3.3.2 Thermal conductivity of the ground

While the thermal conductivity of geological material can range from approximately 0.5 to 6 W/m/K, it usually lies in the range of 1.5 to 4.5 W/m/K (Hellström 1991), as studied here. The thermal gradient between BHE and background lessens when thermal conductivity increases, which can be observed as a larger plume (ca. 35% larger at 9 °C) and steeper temperature gradients close to the BHE (Figure 3.6). Thus, the plume scale disturbed-temperature zone enlarges but the local disturbance near the BHE, which is closely linked to system performance, subsides. The temperatures at the borehole wall are 1-1.5 °C improved.

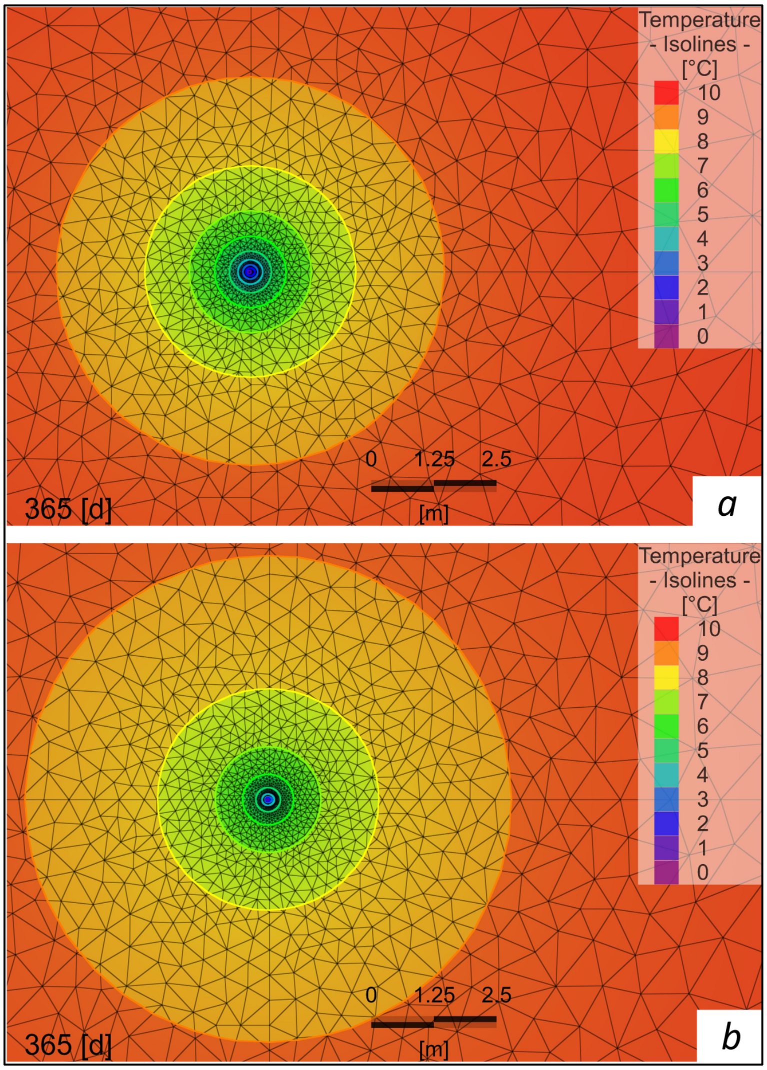

Figure 3.6 Thermal plumes under the subsurface thermal conductivity increased from (a) 1.5 J/m/s/K to (b) 4.5 J/m/s/K after 1 year showing growth in size regionally and shrinkage locally.

As the loop temperatures confirm, there is a direct relationship between thermal performance of the BHE and thermal conductivity (Figure 3.7). The 25-year loop temperature gain nearly doubles when thermal conductivity of solids increases from 1.5 to 4.5 W/m/K. The calculated average specific heat extractions over 6 months and 25 years also shows a doubling rise both in the short-term and long-term, indicating the importance of subsurface thermal conductivity (Table 3.4). Therefore it is essential to know the thermal conductivity of ground as accurately as possible to have a proper BHE design.

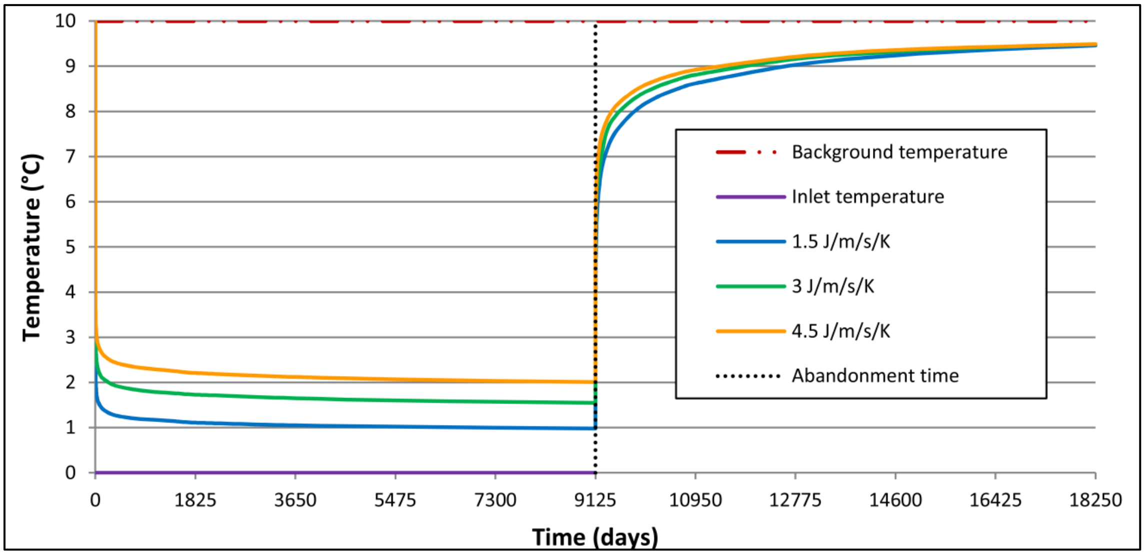

Figure 3.7 Loop outlet temperature vs. time under different thermal conductivities of the subsurface during operation and after abandonment.

Thermal conductivity has an analogous but significantly weaker impact on the temperatures in the recovery phase (Figure 3.7). This is because the thermal gradient between heat exchanger and the surrounding, which is the driving force for the heat transfer by conduction, diminishes when the borehole is shut down. Therefore higher thermal conductivity improves the BHE performance more effectively than it enhances its recovery.

3.3.3 Volumetric heat capacity of the ground

Variation in specific heat capacity influences material's internal energy. The variation in density and especially specific heat capacity in geological media is fairly small (Hellström 1991). By increasing volumetric heat capacity from 1.5×10^6 to 3.5×10^6 $J/m^3/K$, the plume extent radius decreases in regional scale (at 9 °C) by 20%; but the change is subtle locally in contours near the borehole wall (Figure 3.8). Therefore, as the loop temperature results confirm, variations in volumetric heat capacity have an insignificant impact on BHE outlet temperatures under both production and abandonment times (Figure 3.9).

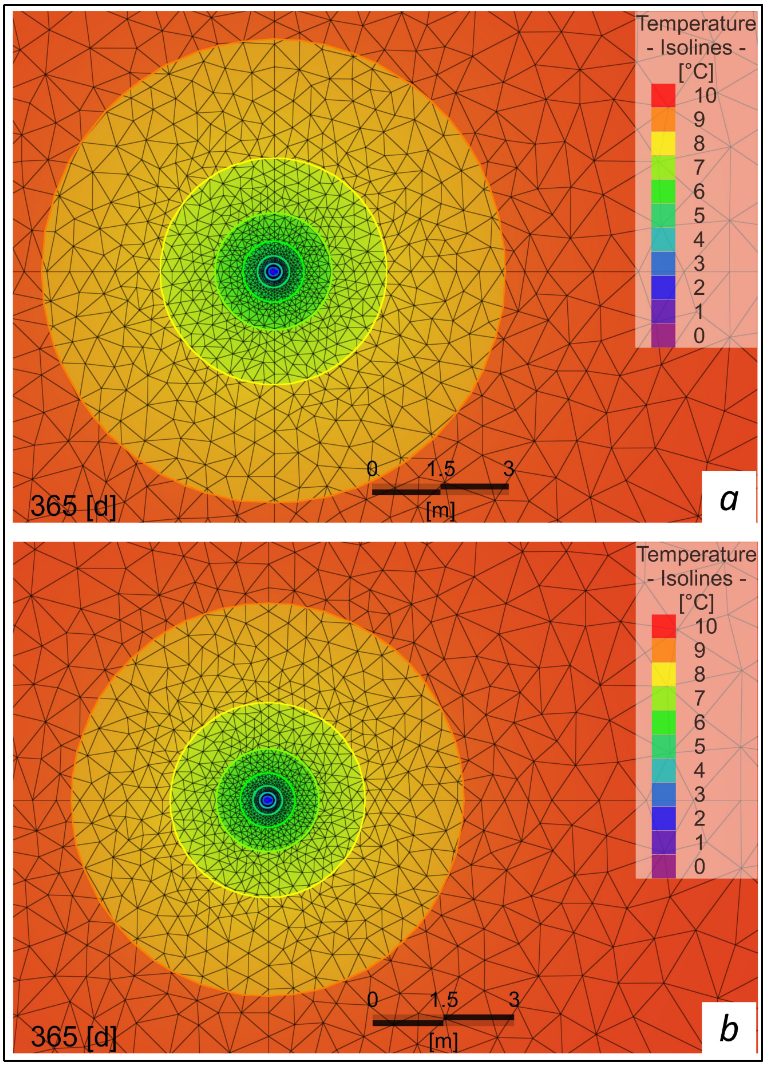

Figure 3.8 Thermal plumes under the subsurface volumetric heat capacity increase from (a) 1.5×10^6 J/m^3/K to (b) 3.5×10^6 J/m^3/K, with 1 year showing more reduction in size regionally than locally.

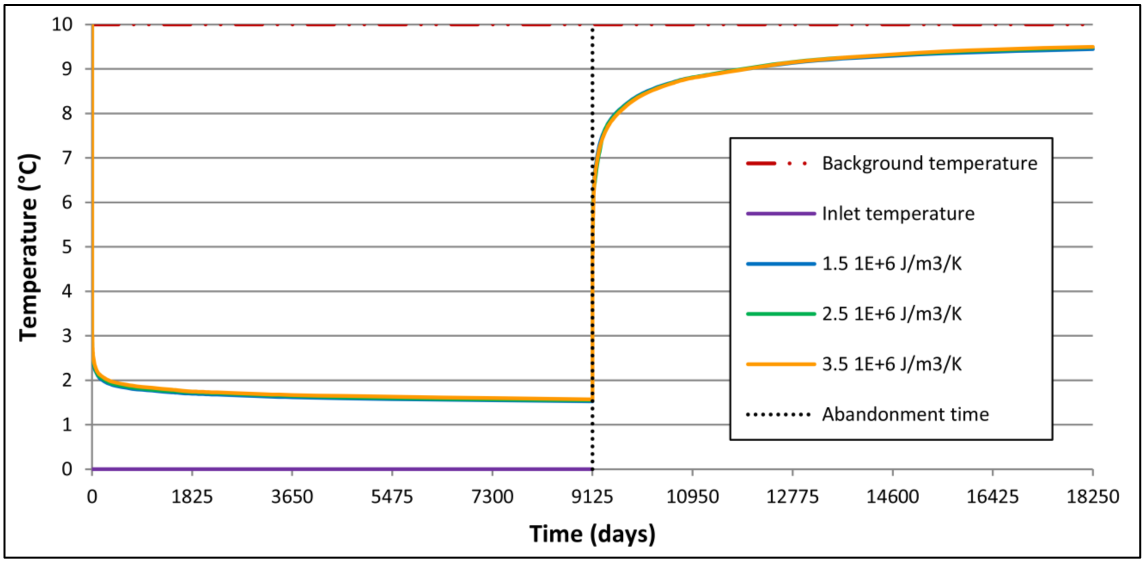

Figure 3.9 Loop outlet temperature vs. time under different volumetric heat capacities of the subsurface during operation and after abandonment.

3.3.4 Porosity of the subsurface

As mentioned in the preceding section 'Sensitivity analysis scenarios and fundamentals', variations in porosity affect advective heat transport only if the pore velocity remains constant; under the constant *q* assumption of this study, porosity is solely influencing the heat transport by conduction. Bulk volumetric heat capacity and thermal conductivity are functions of porosity. Geological material in general has higher heat conductivity and lower volumetric heat capacity (i.e. higher thermal diffusivity) than water. The results show more loop temperature gain and heat extraction rates in less porous material – under the same groundwater flux (Figure 3.10 and Table 3.4). The significance of advective transport will vary under different groundwater fluxes. The less porous subsurface also shows slightly faster thermal recovery. While porosity and hydraulic conductivity are often functionally dependent within the same type of geological material, here for the sensitivity analysis, porosity is varied independently from hydraulic conductivity. However, as the earlier results (see section 'Groundwater flux') showed, at velocities below 10^{-7} m/s, order of magnitude the difference can be overlooked.

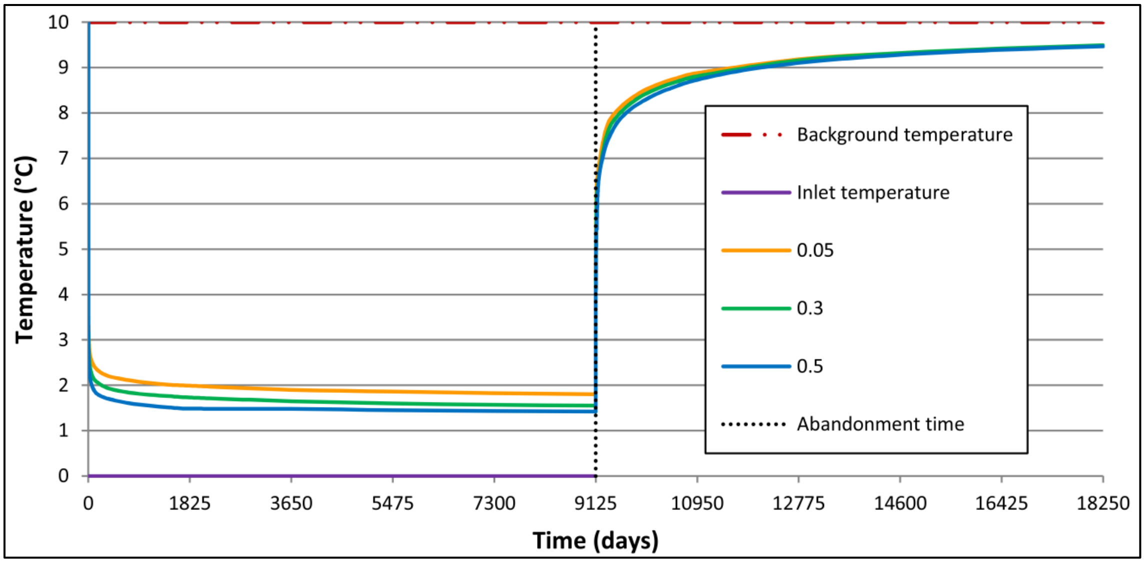

Figure 3.10 Loop outlet temperature vs. time under different subsurface porosity values during operation and after abandonment.

3.3.5 Thermal dispersivity of the subsurface

Dispersivity values are selected based on the scale of the BHE problem with a ratio of α_L/α_T=10. With the studied base groundwater flux (10^{-9} m/s via the hydraulic conductivity and gradient in the base scenario), the loop outlet temperatures (Figure 3.11) appear not to be sensitive to thermal dispersivity values. Although, as previously discussed, the significance of thermal dispersivity rises as groundwater flow rate increases. At the 10^{-6} m/s groundwater flux, the effect of thermal dispersivity is obvious. Increasing the longitudinal thermal dispersivity from 0.1 m to 1 m (α_L/α_T=10) raises the thermal efficiency by about 20% (Figure 3.11). However, precise quantification of dispersivity is a problematic task as it generally reflects our lack of exact knowledge, or representation of, heterogeneity in the permeability and thermal property fields.

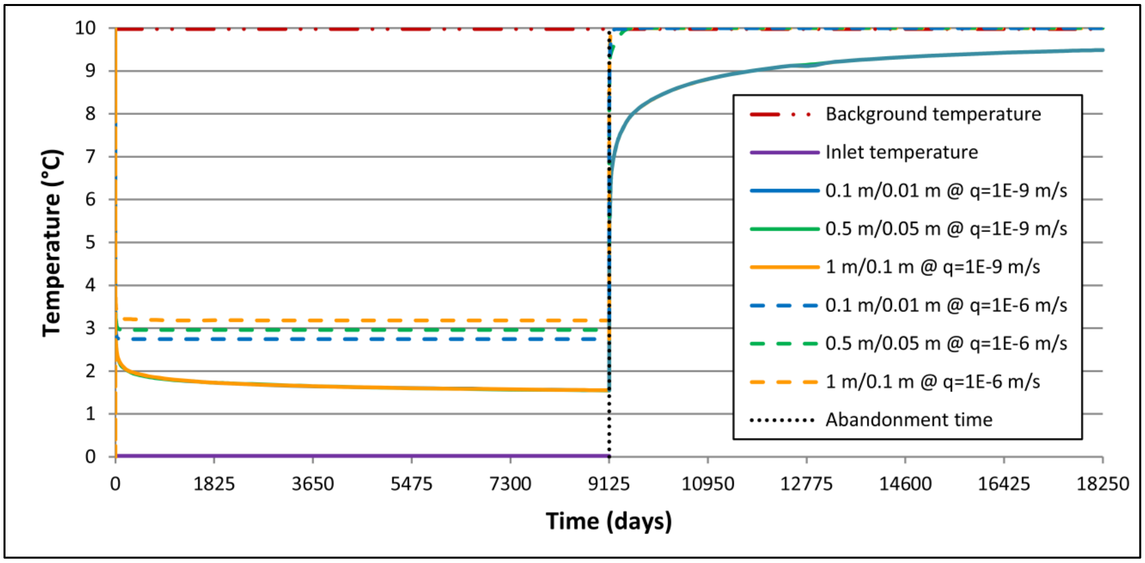

Figure 3.11 Loop outlet temperature vs. time under different subsurface longitudinal/transverse thermal dispersivity values during operation and after abandonment.

In any case, thermal dispersion remains controversial and necessitates further study. Some studies assume that thermal and solute dispersivity have the same order of magnitude (deMarsily 1986; Molson et al. 1992). Vandenbohede et al. (2009) found that thermal dispersivity is smaller than solute dispersivity and that scale dependency is less important; although, there are other studies which conclude that the effect of thermal dispersivity is negligible compared to conduction and set thermal dispersivity to zero (Hopmans et al. 2002; Hutchence et al. 1986). As mentioned in the 'Introduction', the relationship between thermal dispersivity and groundwater flow is debatable, although recent studies (e.g. Ferguson 2007; Hidalgo et al. 2009) confirm that connection; however the spatial heterogeneity in thermal properties seems to be less important than that of permeability (Ferguson 2007). Considering the relationship between dispersion and groundwater flow and the inaccuracy in related parameters, e.g. hydraulic conductivity, thermal dispersivity becomes less important.

3.3.6 Grout thermal conductivity

Thermally enhanced grout is known to have a positive impact on efficiency of geothermal heat-pump systems as it enhances the heat exchange between the BHE and the surrounding ground. This is a similar effect as that of the subsurface thermal conductivity. According to the results, modification of the grout thermal properties does alter the BHE efficiency (Figure 3.12). The results in Table 3.4 indicate that thermally enhanced grout (*λ*=3 W/m/K) increases heat extraction by more than 10% compared to a grout with poor thermal conductivity (*λ*=1 W/m/K). However, this influence is limited compared to that of the ground thermal conductivity which can increase the performance by ca. 100% (Table 3.4); nevertheless, it does not contradict the importance of proper grout selection. While ground thermal properties are not controllable, other than through siting the borehole, grout type is generally by choice. A thermally enhanced grout reduces the thermal gradient – similar to ground thermal conductivity – in immediate proximity of the tube and borehole, which makes the heat exchange more efficient.

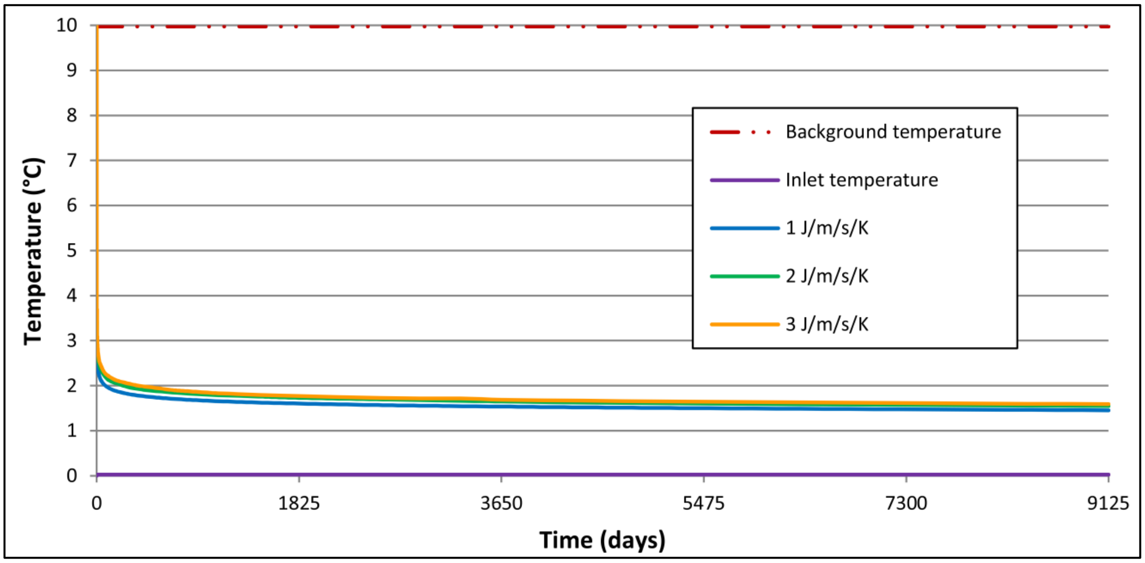

Figure 3.12 Loop outlet temperature vs. operation time for grouts with poor (1 J/m/s/K) and average (2 J/m/s/K) thermal conductivity as well as thermally enhanced grout (3 J/m/s/K).

3.3.7 Background and inlet temperatures

Although the ground temperatures may be relatively accurately known in every region, they may vary by a few degrees in time or from locale to locale. The sensitivity analysis results show that a 2.5 °C deviation of the average background temperature around the presumed value of 10 °C (25%) changes the heat extraction rate by ca. 25% (Figure 3.13

and Table 3.4). This implies that it is critical for a sustainable BHE design to know the background temperature accurately.

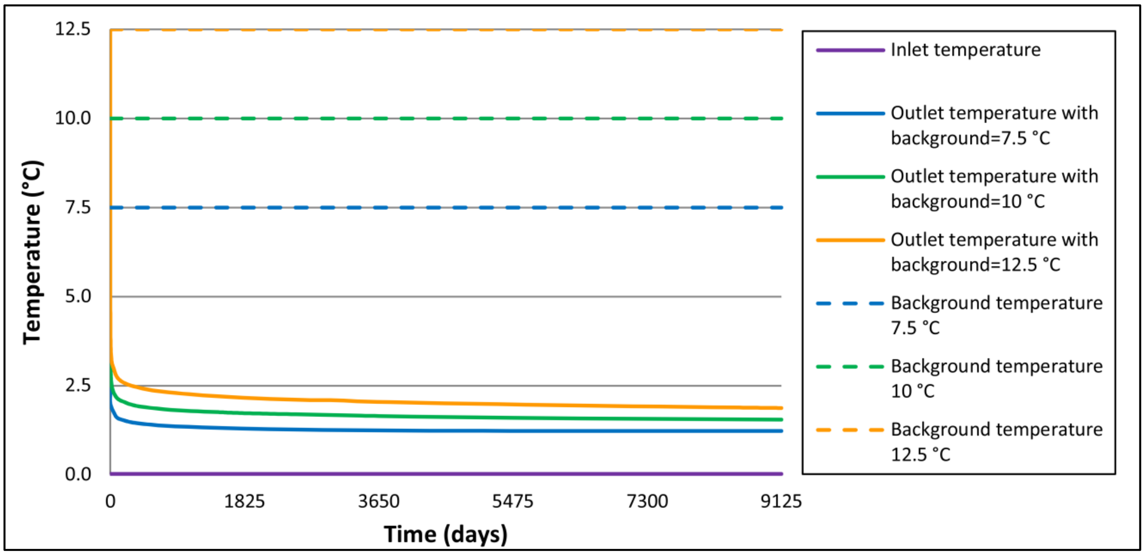

Figure 3.13 Loop outlet temperature vs. operation time under different background temperatures.

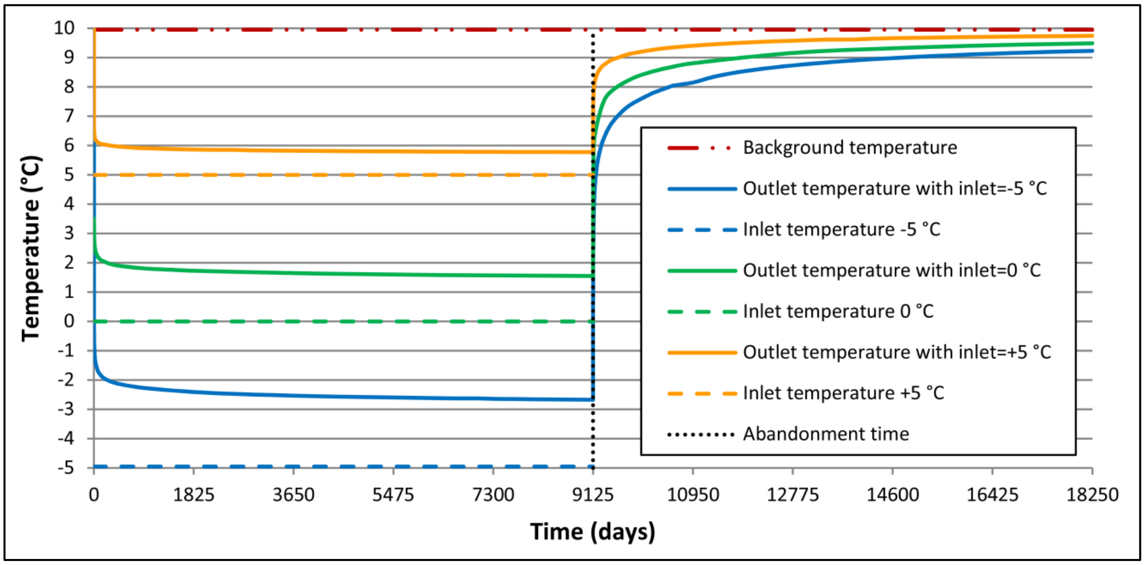

Figure 3.14 Loop outlet temperature vs. time under different inlet temperatures during operation and after abandonment.

Under extreme weather conditions, i.e. peak loads, a geothermal system may have to operate for longer times in order to deliver the required energy, and the heat pump COP (coefficient of performance) will fall. Conversely, the underground portion of the system performs more efficiently when inlet temperatures are farther from the underground background temperatures. This is because the thermal gradient between loop temperature and borehole wall is an essential element in BHE heat exchange. The results confirm that decreasing the inlet temperature from +5 °C to 0 °C and further to -5 °C, radically increase the heat exchange efficiency (Figure 3.14). Borehole fluid temperatures are directly related to the heat extraction rates. The heat extraction rate with -5 °C inlet temperature is about triple that with +5 °C (Table 3.4); however, excessive temperature changes are prohibited under some guidelines – e.g. VDI 4640-2 (VDI 2001). Comparing the plumes in the two cases proves that the BHE thermal load has a distinct influence on the extent of its thermal impact zone (Figure 3.15). The difference in recovered temperatures is about 2 °C after 1 year and 0.5 °C after 25 years despite the initial 10 °C difference in loop temperatures (Figure 3.14). This means that although the recovery time is affected by the loop temperatures, it is not very sensitive to them in the long-term. However based on the preceding results, the 0.5 °C change in background temperature is expected to correspond to 5% change in system performance.

It should be noted that FEFLOW® is unable to model multiple water phases and the latent heat for phase change. However, freezing the ground by lowering the temperature below zero during the heating season is a possible practice. Ground freezing may also result in environmental and geotechnical concerns. Also the volume expansion of freezing water can damage the heat exchanger pipes and modify the contact between grout encased pipe and the borehole wall. The latent heat of water-ice phase change (80 cal/g) improves the energy storage, which also keeps temperatures near the borehole closer to the groundwater freezing point for longer times thereby lowering the thermal gradient drop between BHE and surroundings. Additionally, thermal diffusivity of ice is about 8 times that of water at 0 °C (James 1968). All these effects indicate even better thermal performance in reality compared to the FEFLOW® modelled results at below zero temperatures and ground freezing. Analyzing the data provided by Nordell and

Dikici (1998) confirms that below-zero air temperature results in higher energy extraction rates, while the loop temperatures stay at 0 °C.

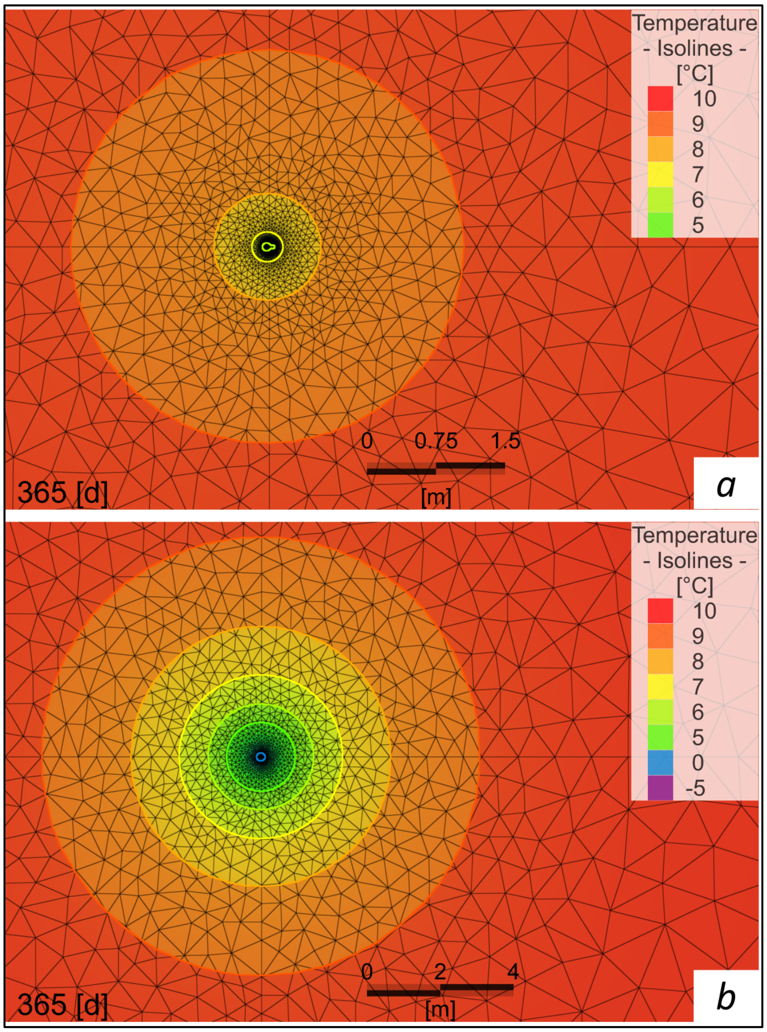

Figure 3.15 Thermal plumes under inlet temperatures (a) +5 °C and (b) -5 °C after 1 year showing significant difference. Note the scale difference.

3.4 Conclusions

During the BHE operation, temperatures stabilize slower far from the borehole, i.e. the plume keeps growing, compared to near-BHE temperatures. The analysis shows that generally the ground temperatures (thermal plume) are more sensitive to changes than the loop temperatures. Thus, accurate assessment of the subsurface properties is more important concerning the BHE's impact zone than its thermal performance. After shutting the system, extreme temperatures in the domain diminish the quickest and the rate of recovery slows down as temperatures reach that of the background. Moreover, the response to the borehole shut-down and thermal recovery may occur with delay far from the BHE, which is important in respect to controlling and reversing different environmental and thermal impacts.

Of the parameters analyzed in this study, the most important factors for BHE design include inlet and background temperature (i.e. temperature gradient), thermal conductivity of the ground and Darcy velocity. Increased groundwater flow can substantially reshape and dissipate the thermal plume by altering the heat transport by enhancing advection and dispersion processes; it also reduces the time to reach steady-state conditions. The impact becomes progressively more observable by every order of magnitude increase in the groundwater flux. It becomes noticeable in loop temperatures at velocities above 10^{-7} m/s range and is substantial at 10^{-6} m/s level. Darcy velocities in this range – 10^{-7} m/s and higher – cannot be disregarded as they also have a substantial impact on the plume shape and size. In a comparable way, but more effectively, groundwater flow enhances thermal recovery to initial conditions; the impact is noticeable in fluxes over 10^{-8} m/s. Groundwater flow proved to be the most important factor in thermal recovery.

Higher thermal conductivity of the ground solids greatly heightens the thermal efficiency of a BHE by improving the heat transport; conversely, it causes larger thermal plumes. Since the thermal gradient drops severely and quickly when the BHE is shut down, thermal conductivity has a relatively minor impact on thermal recovery. While enhancing the thermal conductivity of the grout also increases the borehole specific heat extraction, this effect is more limited in extent. Thus, the choice of using a thermally enhanced grout is more governed by balancing the costs, and changes in the grouts non-thermal characteristics (e.g. placement viscosity, sealing), along with efficiency gains.

Thermal impact of the volumetric heat capacity of soil solids on functioning of BHE and its thermal recovery is negligible. However, there is an inverse relation between subsurface volumetric heat capacity and the plume size.

Thermal efficiency did not appear to be sensitive to thermal dispersivity values at the scale of a BHE domain at low groundwater velocities, i.e. 10^{-9} m/s, but becomes more sensitive only at higher rates, i.e. 10^{-6} m/s. Nonetheless, accurate measurement of thermal dispersivities in situ is often not possible.

Under constant groundwater flux, e.g. this study, increasing the porosity as an individual factor can have a negative impact on a heat exchanger's performance by deteriorating subsurface bulk thermal properties, i.e. conductive heat transport. Comparing cases with equal pore velocities, higher porosity will also imply more heat transport by advection. The natural link between porosity and hydraulic conductivity has to be considered but can be neglected in velocities under 10^{-7} m/s.

The current ground temperature should be accurately known prior to the BHE installation in order to assure a thermally sustainable design and performance. Under short periods of extreme hot and cold weather conditions when a geothermal system has to deliver more heating load and the heat pump COP drops, peak inlet temperatures far from the background temperature boost the heat exchange between BHE and the ground. However changes in the loop fluid temperature may be undesirable in the long-term as the thermal impact zone extent is sensitive to the heat extraction/input rates (i.e. loop fluid temperatures). At the lower end where temperatures fall below zero, freezing the groundwater can further enhance the energy exchange and storage. Although the duration and rate of thermal recovery depend on loop temperatures, a thermal recovery time equal to the operation time appears to be a good estimation for ground temperatures to return close to the initial state, i.e. within 1 °C.

Finally, while closed-loop BHEs do not have the potential for large environmental impacts, or direct strong reliance on groundwater flow that open-loop heat exchangers do, they demand increased attention by hydrogeologists and regulators. Currently, regulations that impose guidelines on temperature thresholds and minimum distance criteria for thermal alterations, or recognize the inherent variability in geologic material thermal properties, are largely lacking, which includes not explicitly addressing the effect of groundwater advection on effective thermal conductivity and recognizing at what groundwater velocities advection becomes important. This has led to BHE design methodologies that often exclude heat transport by groundwater advection. This study clearly shows that quantifying the thermo-hydrogeological parameters in vertical closed-loop BHEs supports the design of sustainable efficient systems while addressing the impacts on down-gradient BHEs or water supply and ecological features.

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Chapter 4

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

4.1 Introduction

Ground source heat energy is becoming increasingly popular as a source of renewable energy for comfort heating and cooling of buildings. 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. Subsurface effective thermal conductivity consists of two components: bulk thermal conductivity of the aquifer (conductive heat transport) and groundwater flow (advective heat transport). The point at which advective heat transport becomes important compared to the purely conductive case can be governed by the thermal Péclet number as a function of solid/fluid thermal properties and groundwater flux (Anderson 2005). However, using groundwater flow rate is more precise as it is not dependent on supplementary parameters such as characteristic length (Chiasson et al. 2000). Values for Darcy velocity, and 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 2013; Fuji et al. 2005). Groundwater flow can reduce BHE installation length and cost (Wang et al. 2012). However, as many BHEs are currently designed based on energy load only, i.e. no groundwater flow, the designed loop may not function optimally. Therefore including groundwater flow in the design procedure can be essential for thermal and economic sustainability of the system.

Thermal sustainability of a single BHE is primarily independent of the thermal load seasonal 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. Under a 50 W m^{-1} specific heat extraction rate they suggest a minimum spacing of 7-8 m.

Typically, the presumption of negligible groundwater advection and domination of conductive transport dominates the research literature and governs the design procedure. However, the effect of groundwater advection on heat transport and BHEs is known and 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 (Chiasson 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 Fuji et al. (2005), Péclet numbers higher than 0.1 (associated with ca. 10^{-7} m/s groundwater flow rate) enhance the heat extraction rate. Lee and Lam (2009) estimate the influence of groundwater velocity on thermal response test (TRT) at velocities over 2×10^{-7} m s^{-1}. Advective heat transport by groundwater may alter the temperature distribution, and decrease temperature disturbance, near the BHE allowing a steady-state condition to be reached more quickly (Diao et al. 2004). Dehkordi and Schincariol (2013) performed sensitivity analyses on thermal and hydrogeological ground properties and ranked groundwater flow amongst 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^{-1}).

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 Hemmingway (2012) modeled single and 4×1 BHEs with unbalanced heating load under pure conduction and partial conduction-advection (with 1.85×10^{-6} m s^{-1} 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 6×10^{-8} m s^{-1}

groundwater velocity (Pé=0.02) reduces the thermal disturbance and accelerates reaching steady-state conditions. Choi et al. (2013) modeled 9 BHEs in line, L-shaped and square arrays under different groundwater directions. Their results show that line-type array is noticeably influenced by groundwater direction while square array is almost unresponsive to it. However, Choi et al. (2013) suggest further research on the role of energy load.

In many cases the energy demand of the building 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 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). Balance in energy loads can also be simply a result of symmetry in heating/cooling demands and climate (e.g. Polizu and Hanganu-Cucu 2010). The benefits of having a balanced energy load can be so great that even 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 trading the energy (Banks 2012). However, generally in borehole thermal 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 5-10 m), in BTES systems boreholes are more densely located to optimize the storage and retraction 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 evaluates the effect of groundwater on thermal interference between the boreholes and the overall performance of multi-BHE systems. The configuration of the BHEs (number, layout and separation) will also be examined in this regard. All the analyses 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.

4.2 Method and Modeling

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

$$\frac{k}{\rho c}\nabla^2 T = \frac{\partial T}{\partial t} \tag{4.1}$$

Symbols used in Equation 4.1 (and the following Equations 4.2-4.4) are presented in Table 4.1. In a hydrogeological context, bulk volumetric heat capacity (Equation 4.2) and bulk thermal conductivity (Equation 4.3) of the aquifer can be assigned:

$$\rho' c' = n\rho_f c_f + (1-n)\rho_s c_s \tag{4.2}$$

$$k' = \varepsilon_f k_f + \varepsilon_s k_s \tag{4.3}$$

For the case of flowing groundwater the advection component can be added to keep the energy equilibrium; the equation can be written as (after Domenico and Schwartz 1998):

$$\frac{k'}{\rho' c'}\nabla^2 T - \frac{\rho_f c_f}{\rho' c'}\nabla(T\,q) = \frac{\partial T}{\partial t} \tag{4.4}$$

Table 4.1 Nomenclature and units.

Symbol	**Parameter**	**Unit**
c	Specific heat capacity	J kg^{-1} K^{-1}
c'	Bulk specific heat capacity	J kg^{-1} K^{-1}
k	Thermal conductivity	J m^{-1} s^{-1} K^{-1}
k'	Bulk thermal conductivity	J m^{-1} s^{-1} K^{-1}
n	Portion of volume in each	-
q	Darcy flux	m s^{-1}
t	Time	s
T	Temperature	°C
Greek letters		
ρ	Density	kg m^{-3}
ρ'	Bulk density	kg m^{-3}
Subscripts		
f	Fluid	-
s	Solid	-

The modeling is performed in FEFLOW®, a three dimensional (3D) finite element (FE) fully coupled variable density groundwater flow and transport code. The BHE solution used in this paper, was developed by Diersch et al. (2010, 2011a, 2011b) based on Eskilson and Claesson’s (1988) analytical solution. 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). Properties of the modeled BHE(s) are tabulated in Table 4.2.

Table 4.2 Borehole and ground material properties in all models.

Parameter	**Value and Unit**
Borehole depth	100 m
Borehole diameter	0.15 m
Pipe distance	0.075 m
Pipe diameter	0.048 m
Pipe thickness	0.004 m
Dynamic viscosity of refrigerant	0.52×10^{-3} kg m^{-1} s^{-1}
Thermal conductivity of refrigerant	0.48 J $m^{-1}s^{-1}$ K^{-1}
Heat capacity of refrigerant	4000 J kg^{-1} K^{-1}
Density of refrigerant	$1.052\times10^{+3}$ kg m^{-3}
Flow discharge of refrigerant	25 m^3 d^{-1}
Thermal conductivity of grout	1.5 J m^{-1} s^{-1} K^{-1}
Thermal conductivity of pipe	0.475 J m^{-1} s^{-1} K^{-1}
Porosity	0.3
Volumetric heat capacity of groundwater	$4.2\times10^{+6}$ J m^{-3} K^{-1}
Thermal conductivity of groundwater	0.65 J m^{-1} s^{-1} K^{-1}
Volumetric heat capacity of ground solids	$2.52\times10^{+6}$ J m^{-3} K^{-1}
Thermal conductivity of ground solids	3 J m^{-1} s^{-1} K^{-1}

Initially a single BHE is modeled with no groundwater flow and 10^{-7} m/s flow rate (See ‘Introduction’) conditions under both balanced and unbalanced energy loads as the benchmark for comparison with BHEs in grids. The balanced and unbalanced energy loads for 1 year are shown in Figure 4.1 and are repeated over the entire simulation period of 25 years. In both cases the peak specific heat extraction/injection rate is equal, 50 W m^{-1}. Additionally 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 with (10^{-7} m s^{-1} Darcy flux) and without groundwater flow, and under both energy loads. 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 4.1 is also modeled. In the BTES a smaller borehole separation, 2.5 m, 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 m^3 d^{-1} fluid discharge rate throughout the year. For a summary of the simulations please refer to Table 4.3.

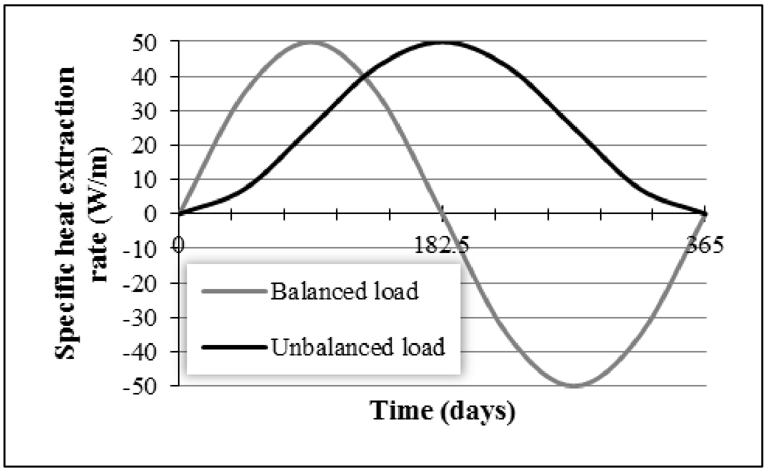

Figure 4.1 The balanced and unbalanced energy loads used in the simulations.

Table 4.3 Summary of simulation combinations.

BHE array	Groundwater flow rate (m s^{-1})	Thermal load	Spacing (m)
1	0	Balanced	7.5 m
		Unbalanced	7.5 m
	10^{-7}	Balanced	7.5 m
		Unbalanced	7.5 m
2×1	0	Balanced	7.5 m
		Unbalanced	7.5 m
	10^{-7}	Balanced	7.5 m
		Unbalanced	7.5 m
4×1	0	Balanced	7.5 m
		Unbalanced	7.5 m
	10^{-7}	Balanced	7.5 m
		Unbalanced	7.5 m
2×2	0	Balanced	7.5 m
		Unbalanced	7.5 m
	10^{-7}	Balanced	7.5 m
		Unbalanced	7.5 m
4×4	0	Balanced	7.5 m
		Balanced	5 m
		Unbalanced	7.5 m
		Unbalanced	10 m
	10^{-7}	Balanced	7.5 m
		Balanced	5 m
		Unbalanced	7.5 m
		Unbalanced	10 m
4×4	0	BTES	2.5 m
	10^{-7}		2.5 m

4.3 Results and Discussion

4.3.1 Effect of energy load and BHE array configuration

To compare the performance of BHEs in different array types (line and square) a constant number of BHEs (four) are modeled which indicates 4×1 and 2×2 arrays. When the average loop temperatures for 4×1 and 2×2 arrays are compared no difference is found under a balanced thermal load (Figure 4.2) implying that the loop temperatures are not affected by the array type. Under the unbalanced thermal load, a decline in average fluid temperature with time occurs in both 4×1 and 2×2 layouts (Figure 4.3). This decline is more evident with the 2×2 layout; suggesting a poorer performance, requirement for larger distance between BHEs compared to the 4×1 arrangement. In this case the difference in performance between the two array types becomes obvious after a few years and increases until it reaches a rather constant quasi-steady state. This confirms sensitivity of thermal performance to borehole array shape under unbalanced thermal loads versus balanced loads. Although there are correction coefficients for designing borehole separation available, they do not account for the balance between heating and cooling loads.

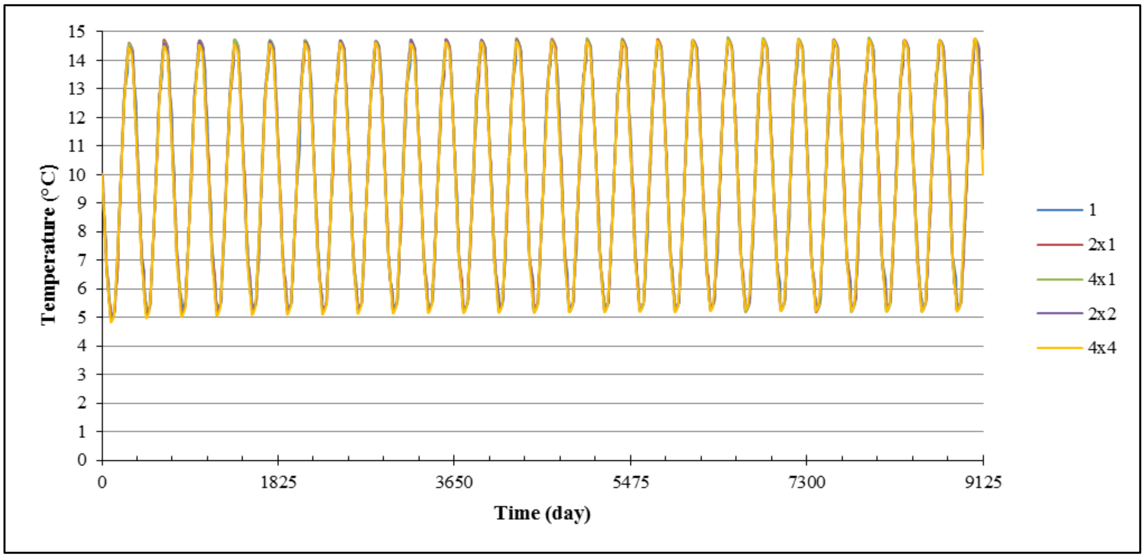

Figure 4.2 Average fluid temperatures in various array types under the balanced energy load and no groundwater flow.

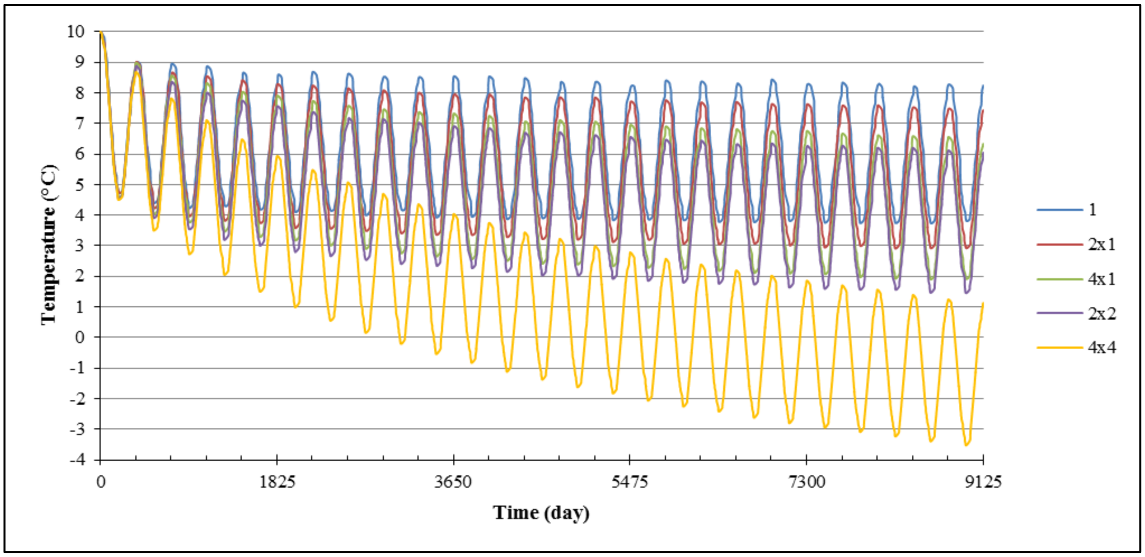

Figure 4.3 Average fluid temperatures in various array types under the unbalanced energy load and no groundwater flow.

The effect of the number of boreholes is examined for both line (2×1 vs. 4×1) and square (2×2 vs. 4×4) layouts. For balanced thermal load, increasing the number of boreholes does not appear to affect loop temperatures. The modeled 2×1, 4×1, 2×2 and 4×4 arrangements all have virtually the same fluid temperatures over the 25 years (Figure 4.2); 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 4×1 array has fluid temperatures lower than those of 2×1 array (Figure 4.3). Compared to a single BHE, the two arrays show approximately 2.2 °C and 1 °C drop in minimum fluid temperature, equivalent to 55% and 25%, in the 25th year. The magnitude of difference between fluid temperatures is increasing until they reach quasi-steady state. Figure 4.3 shows that a square arrangement is more adversely affected by the increase in number of boreholes. The time to reach a pseudo steady-state condition also significantly increases and the system may experience an essentially ever-falling performance (4×4). Therefore, as the systems become larger 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 an unbalanced-load system experiences an inevitable deterioration in performance with time 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, specific heat extraction rates can be modified through increasing the BHE depth which however, will add to the cost. In order to see the effect of borehole spacing the distance between boreholes is reduced in the balanced-load case and increased in the unbalanced-load case; both by 2.5 m (Figure 4.4). In both instances, the impact is observed in loop temperatures as early as the first year. However, under the balanced-load there is no long-term sustainability concern and although a drop in performance occurs it remains stable with time. Under the unbalanced load, increase in BHE spacing decreases the temperature drop and shortens the stabilization time. 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 or inaccurate estimations for borehole depth and separation can introduce large accumulative errors especially given that larger systems are usually intended to operate for long periods of times.

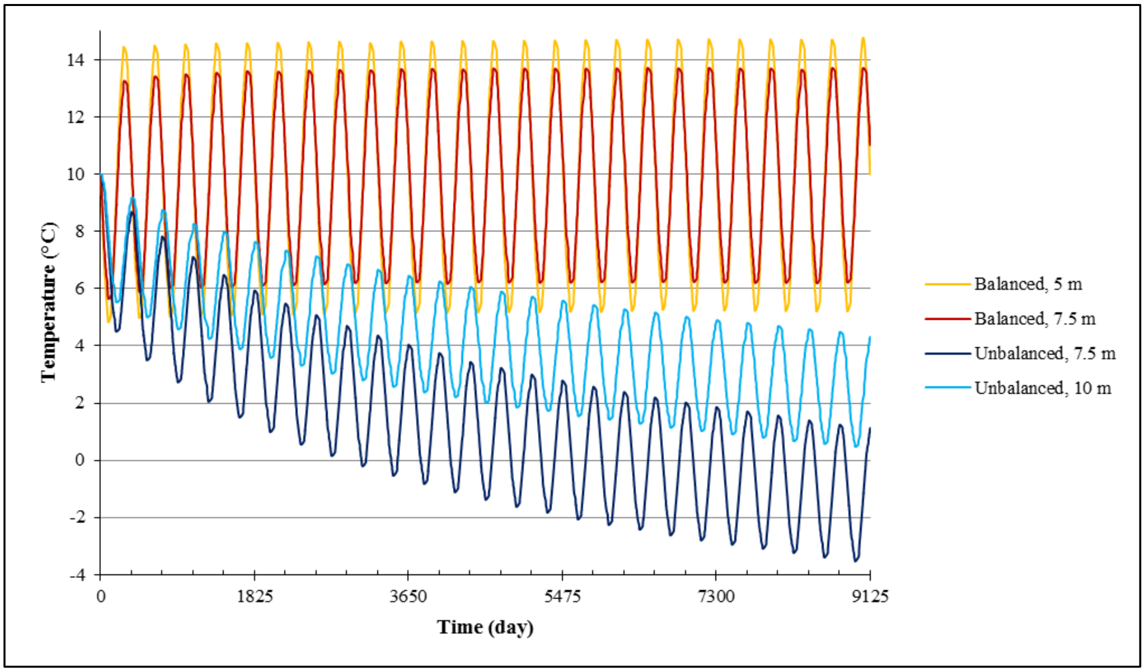

Figure 4.4 Average fluid temperatures in 4×4 square arrays with various BHE separations, balanced and unbalanced energy loads; without groundwater flow.

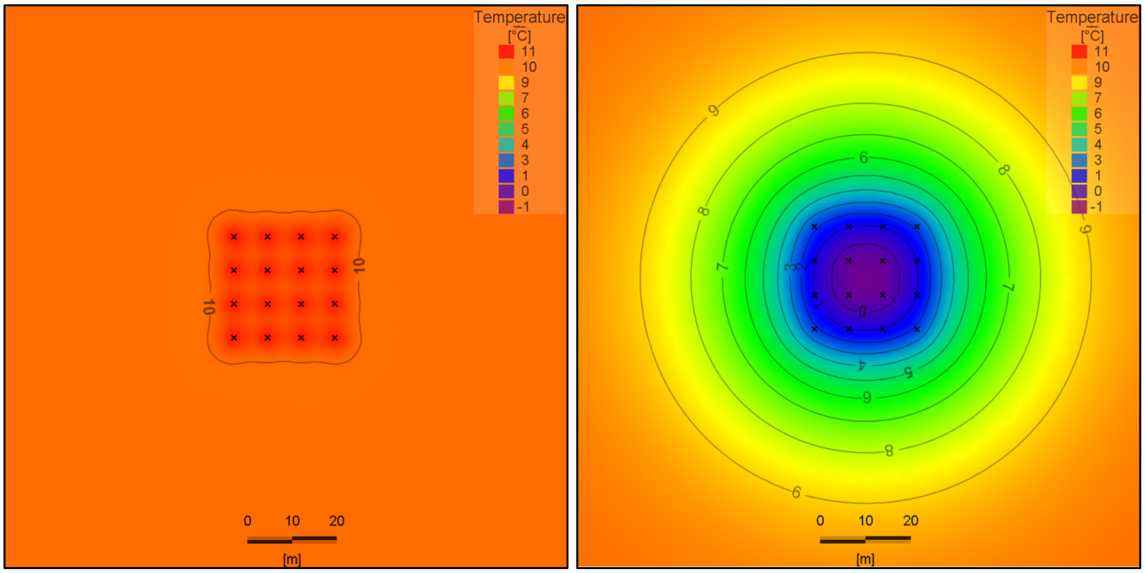

Figure 4.5 Ground temperatures under balanced (left) and unbalanced (right) energy loads with no groundwater flow after 25 years. Note the same temperature and length scales. The cross symbols (×) show the location of BHEs.

From the results above it can be concluded that, balancing the energy load substantially lowers the sensitivity of long-term thermal efficiency and sustainability to the borehole grid configuration, i.e. 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 4.5). After 25 years, a representative design lifetime, the balanced load has led to an almost negligible temperature disturbance (1 °C), which is constrained nearly to the extent of the borehole array. The unbalanced load causes large changes to the ground temperatures extending nearly 50 m in diameter at 9 °C contour (1 °C disturbance). This can in turn negatively impact the performance of neighboring installed systems as well water resources and ecological features.

It can be concluded that balancing the energy load of large multi-borehole systems significantly enhances the performance and greatly moderates the impact. Thus, economically and technically evaluating the possibilities to balance the thermal load during system life time – or at least parts of it – can be of high relevance to guarantee long-term sustainability. This may be achievable by sharing/trading the energy with a larger community or simply "dumping" the excess energy into the subsurface to reach a well-balanced load.

4.3.2 Effect of groundwater flow

As previously mentioned, how groundwater flow impacts a BHE has been fairly well studied; the choice of groundwater flow rate in this paper (10^{-7} m s^{-1}) is based on past studies (e.g. Lazzari et al. 2010) frequently reporting velocities in this range (and higher) to have a noticeable influence on loop temperatures. According to the results by Choi et al. (2013), a line array is more sensitive to 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. In a line array, rotating the flow direction by 90° would cause 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^{-1} groundwater flow rate and compared with the no-flow results. The simulations are then extended to the borehole arrays studied above (i.e. 2×1, 4×1, 2×2 and 4×4). 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.

The balanced-load systems temperatures are insignificantly impacted by groundwater flow; the impact remains constant during all simulation years (Figure 4.6 vs. Figure 4.2). 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 but not when the heating-cooling loads are unbalanced. The thermal plume is also insignificantly impacted by groundwater flow in all balanced-load cases. A perfect natural balance in system load may be an ideal design situation but it is infrequently achieved 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).

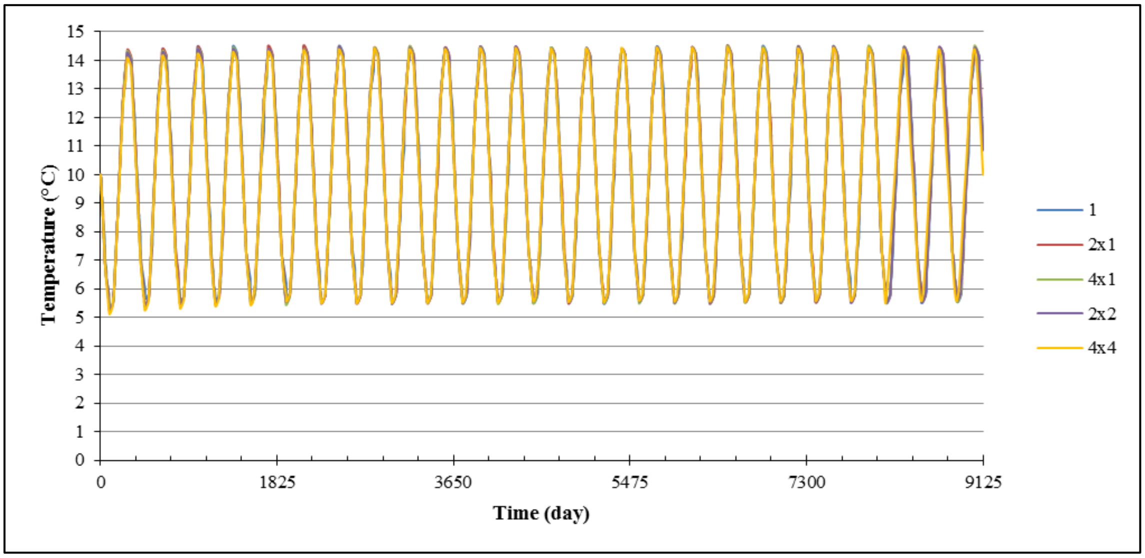

Figure 4.6 Average fluid temperatures in various array types, under the balanced energy load and 10^{-7} m s^{-1} groundwater flow.

Under unbalanced energy load conditions, the decrease in temperatures and thus improvement in performance, is initially minor but accelerates with time as the groundwater flow shortens the time to approach a quasi-steady state (Figure 4.7 vs. Figure 4.3). This increasing difference between the pure conduction (0 m s^{-1}) and conduction-advection (10^{-7} m s^{-1}) conditions becomes more significant from a single BHE to 2×1, 4×1, 2×2 and 4×4. While earlier results showed that a 4×1 array clearly performs better than a 2×2 pattern under unbalanced load in absence of groundwater flow, they perform nearly equally under groundwater flow. As presented in Figure 4.8, comparing the individual BHE temperatures in 4×1 and 2×2 arrays the upgradient borehole in 4×1 array (borehole a) performs better than the boreholes located upgradient in a 2×2 formation (boreholes a, b). Moving downgradient, the BHE in a 4×1 formation experience a drop in temperature due to interference from upgradient BHEs (Figure 4.8). In a conduction-only model, the 1st and 4th BHEs (boreholes a, d) in a 4×1 layout have the best performance while the 2nd and 3rd BHEs (boreholes b, c) perform the worst. 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. The temperature distribution around the BHEs which is directly linked to the loop temperatures confirms these findings (Figure 4.9). A decision on optimal array type and its orientation, while not complicated in itself, requires knowledge of groundwater flow rate and 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.

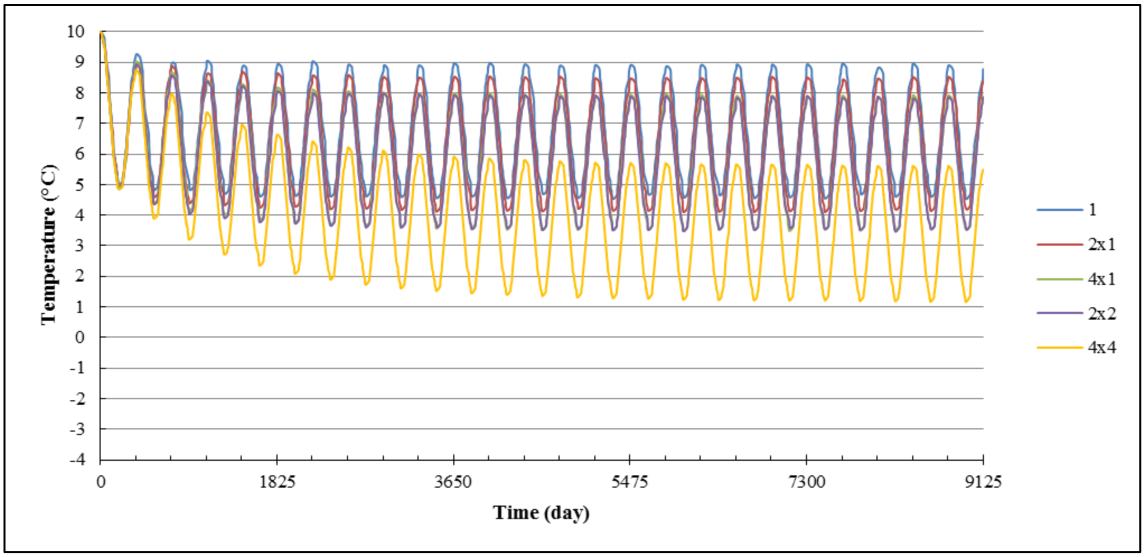

Figure 4.7 Average fluid temperatures in various array types, under the unbalanced energy load and 10^{-7} m s^{-1} groundwater flow.

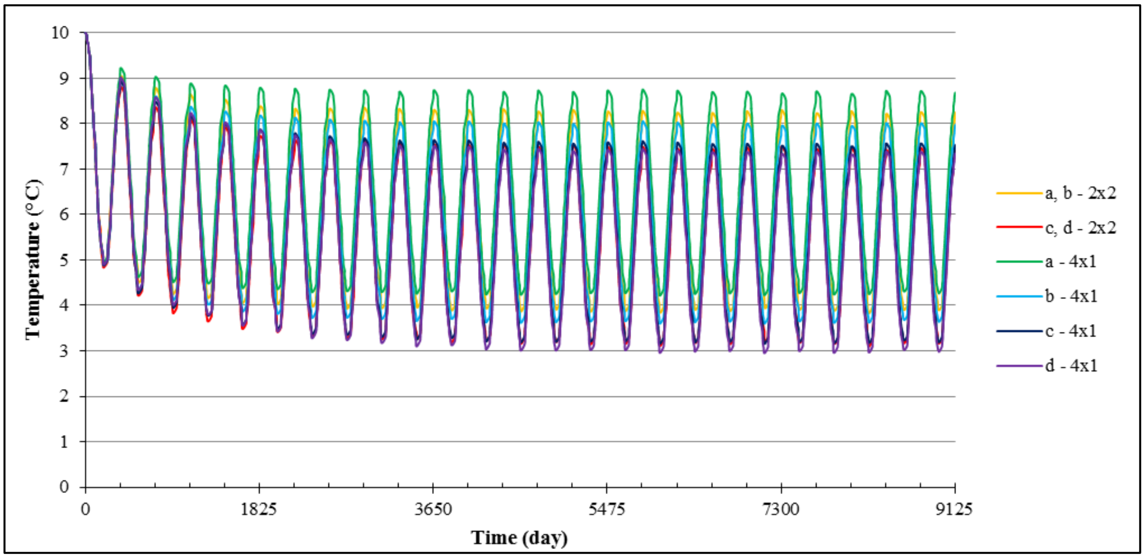

Figure 4.8 Individual BHE loop temperature in 4×1 and 2×2 arrays with unbalanced energy load and 10^{-7} m s^{-1} groundwater flow. Boreholes are named a, b, c, d from upgradient to downgradient.

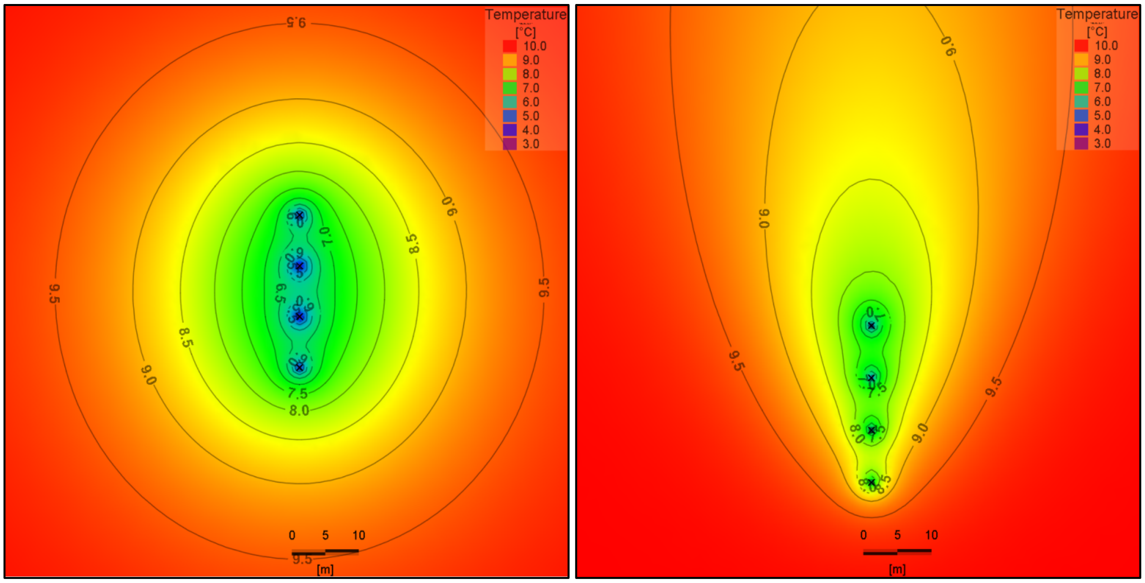

Figure 4.9 Ground temperatures around 4×1 boreholes in the 25th heating season under unbalanced load with no groundwater (left) and 10^{-7} m s^{-1} flow rate (right). Flow direction is from bottom to top of the image. The cross symbols (×) show the location of BHEs.

In the 4×4 array, a large temperature difference, i.e. more than 4 °C, is observed between the upgradient and downgradient BHEs as a result of advection-driven thermal interference (Figure 4.10). Although in the first couple of years no significant improvement is noticed due to enhanced heat transport by groundwater flow, the improvement becomes obvious when the temperatures start to skew towards steady state (Figure 4.7 vs. Figure 4.3). In addition, higher complexity is detected in the ranking of boreholes by their temperature compared to the no-groundwater flow model, with the downgradient BHEs generally performing worse. The time to reach steady state is about 5 years for the upgradient BHEs but becomes nearly double for the downgradient BHEs. 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 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 4.10 vs. Figure 4.5). The advective heat transport by groundwater in large systems can have thermal as well as environmental implications, the significance of which increases in the long-term. Although the reduced temperature differentials and dispersion of the plume tend to reduce the likelihood of some environmental-geotechnical concerns, the thermal plume will be more spread and subject to uncertainty depending on groundwater flow rate and direction. Therefore a hydrogeological study, of sufficient period to capture changes in hydraulic gradients, is important for large multi-borehole systems to ensure optimal system performance, prevent interaction with nearby BHE systems, and to protect groundwater and surface water resources, as well as ecological features.

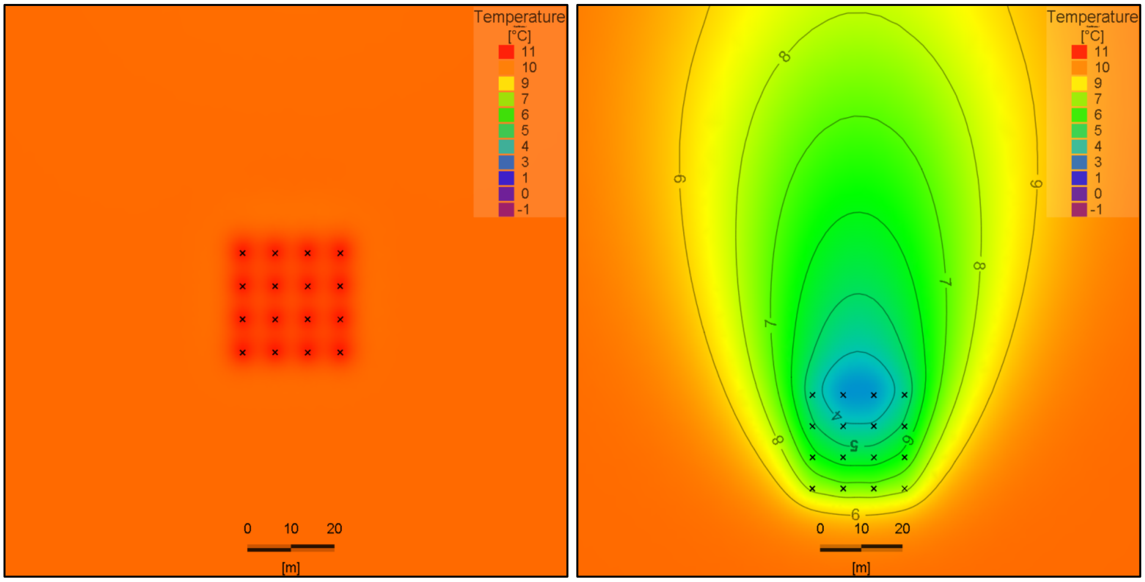

Figure 4.10 Ground temperatures under balanced (left) and unbalanced (right) energy loads, with groundwater flow (10^{-7} m s^{-1}) after 25 years. Note the same temperature and length scales. Flow direction is from bottom to top of the image. The cross symbols (×) show the location of BHEs.

The spacing between the BHEs and groundwater advection 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 4.11). 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 each parameter, i.e. BHE distance and groundwater flow rate. For example, here a 2.5 m increase in the distance has more impact than introduction of 10^{-7} m s^{-1} groundwater flow; this may not be the case if the flow increases more. When the energy load is unbalanced both the borehole separation and groundwater flow become increasingly important in system efficiency (Figure 4.12). However, groundwater flow is more effective in shortening the time to reach quasi-steady state. In the scenarios shown in Figure 4.12, 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^{-1} flow. 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 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.

As cited earlier, the distance between the boreholes is one of the common design factors in multi-BHE systems. Knowledge of the effect of groundwater flow on BHEs has also evolved considerably, especially in the recent years, and the necessity of including the groundwater flow in the design process in certain cases is clear. The results illustrate that groundwater flow can potentially be more important than BHE separation in the long-term and that an optimal BHE distance should be selected in combination with groundwater flow.

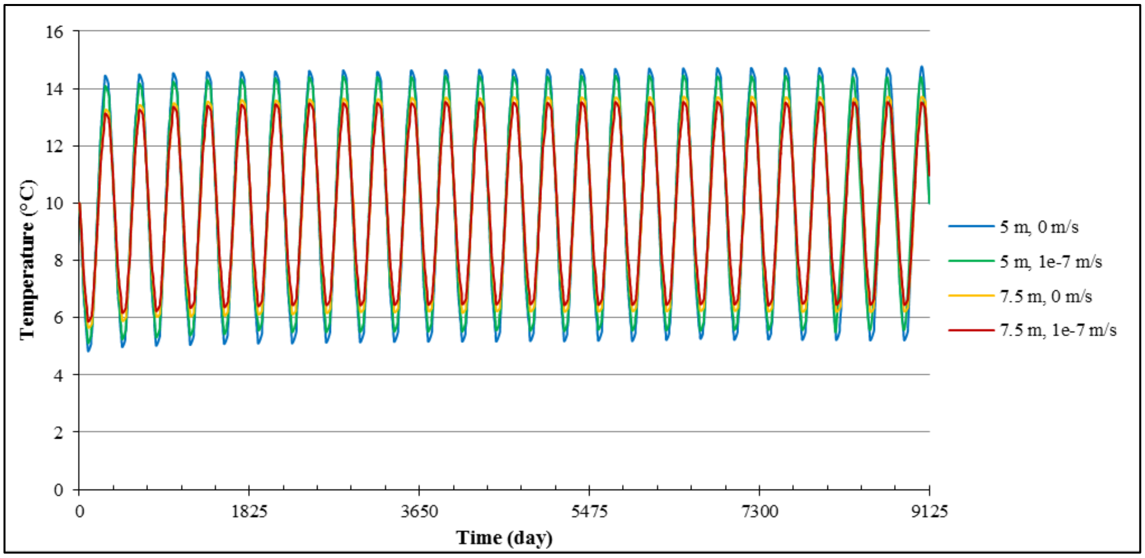

Figure 4.11 Average loop temperatures in 4×4 square arrays with various BHE separations and groundwater flow rates, under balanced energy load.

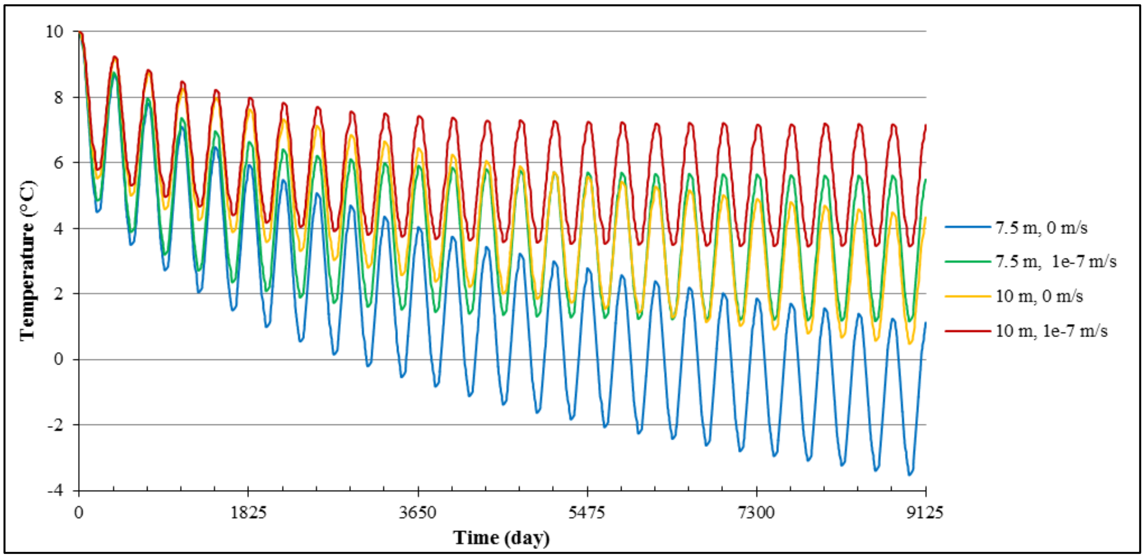

Figure 4.12 Average loop temperatures in 4×4 square arrays with various BHE separations and groundwater flow rates, under unbalanced energy load.

4.3.3 Borehole thermal energy storage systems

Borehole thermal energy storage (BTES) systems work on the same basis as normal BHEs 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 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 4.13). 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^{-1} 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 4.13). 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 (i.e. 2.5 °C and 2.8 °C in the same order). As the loop temperatures indicate, adding the groundwater movement the modeled BTES performs less efficiently during its entire lifetime which worsens with time. Groundwater flow can deteriorate the actual performance of BTES compared to the designed performance not accounting for groundwater flow. In this instance, overlooking the groundwater flow causes a 16 % overestimation in heat production rate at the end of the 25th heating season. The increase in introduction of energy to the subsurface and the subsequent decrease in energy abstraction, caused by groundwater flow, lower the energy efficiency. With more heat being introduced into the underground, the potential for thermal and environmental impacts also increases. Theoretically a virtually infinite amount of energy exists in the subsurface. However, to efficiently extract more of this energy 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.

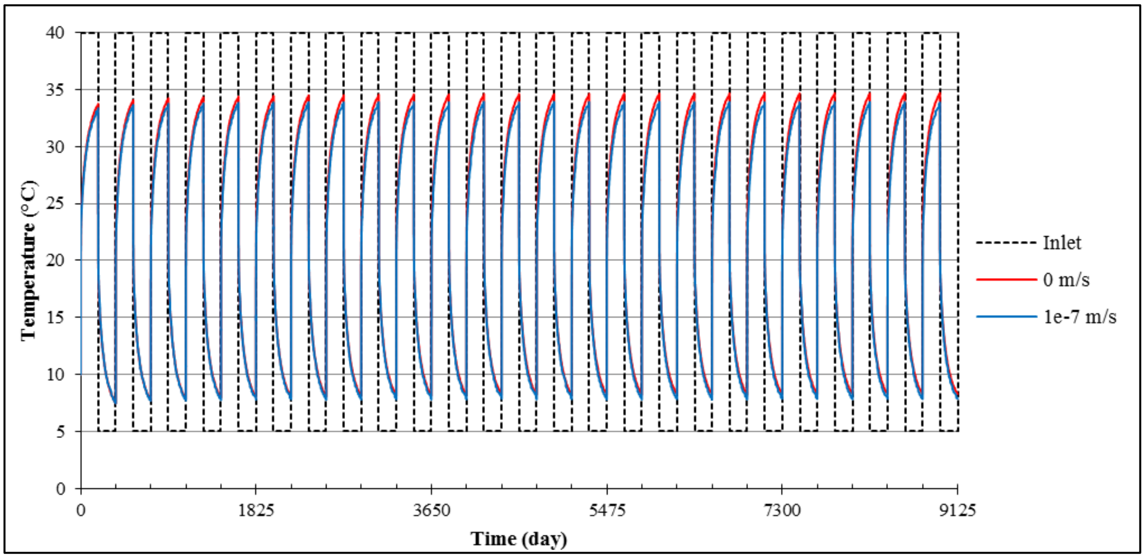

Figure 4.13 Comparison of inlet and average outlet temperatures in the 4×4 BTES, under 0 m s^{-1} and 10^{-7} m s^{-1} groundwater flow.

Comparison of thermal plumes under pure conduction and partial advection-conduction shows that groundwater flow causes a greater impact zone, which spreads well beyond the extent of the BTES in the flow direction (Figure 4.14). Since large temperature gradients are present in BTES systems, the magnitude of the downgradient temperature disturbances is rather high despite the added hydrodynamic dispersion. By the end of the heating season the entire high temperature zone (stored heat) is transported downstream away from the BHEs, becoming unusable and wasted. Note the assigned 10^{-7} m s^{-1} flow rate is at the lowermost reported range for having noticeable impact on thermal response tests and non-BTES systems. Further sensitivity analysis exclusively for borehole thermal energy storage systems may be necessary to find groundwater flow thresholds with regards to storage and extraction temperature gradients.

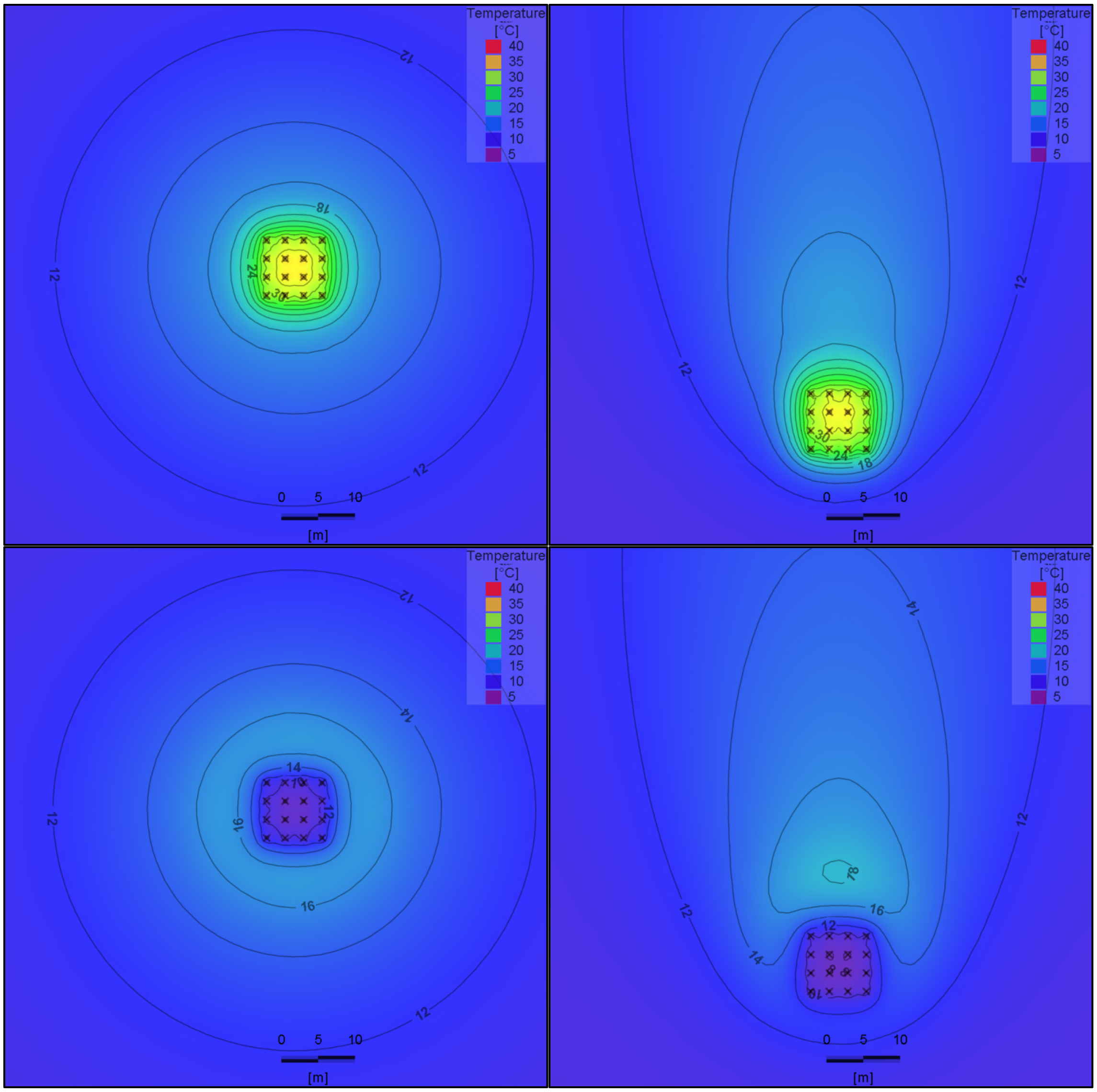

Figure 4.14 Ground temperatures in surroundings of the BTES peaking in the 25th cycle of heat storage (top panels) and dissipating after the extraction in the end of the 25th year (bottom panels) with no groundwater (left) and 10^{-7} m s^{-1} flow rate (right). Flow direction is from bottom to top of the image. The cross symbols (×) show the location of BHEs.

4.4 Conclusions

This study has examined the influence of groundwater flow (0 m s^{-1} versus 10^{-7} m s^{-1}) on BHEs with balanced and unbalanced thermal loads, as well as a BTES system. The effect is analyzed with regards to the average BHE-field temperature, thermal interference between individual BHEs in the field, and the disturbance to subsurface temperatures due to the produced thermal plume.

When the heating and cooling loads are balanced, sensitivity of the performance and 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. In this case the performance fluctuates insignificantly in the long-term. 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 sustainability of BHE systems.

When either the heating or cooling demand is dominant, the sustainability of the design strongly depends on the position and number of boreholes in the grid. The system efficiency and level of disturbance to ground temperatures also highly depends on the separation between boreholes. The efficiency declines and impact continuously deteriorate with time until reaching a quasi-steady state. Therefore, the design lifetime is an essential aspect of system long-term sustainability. If the system has not reached its quasi-steady state within the design period, it will continue experiencing severe reduction in efficiency and may not be serviceable beyond the designed period, unlike when the energy load is balanced or when the quasi-steady state is achieved.

Groundwater flow has little impact on improving the performance of balanced-load systems. In contrast when the energy load is unbalanced groundwater has an ever-increasing influence enhancing the thermal efficiency and reducing generated subsurface temperature anomalies. As the loop temperatures become more extreme, by switching from line to square array and increasing the number of BHEs, groundwater flow becomes more relevant. The results show that the potential for advection-driven thermal interference between the BHEs is higher in a line arrangement – when groundwater flows parallel to its axis – which consequently hinders the enhancement in performance. However, as previous studies have shown BHE thermal interference in line array is sensitive to the direction of flow. Therefore, when the direction of groundwater flow is unknown, varies temporally or spatially in different encountered formations, the design can be more confidently done in square array.

Conversely in BTES systems, groundwater flow can have negative undesired impacts. The example modeled here shows that a modest groundwater flow rate of 10^{-7} m s^{-1} 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 flow rate 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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Chapter 5

5 Effect of horizontal and vertical fractures on borehole heat exchangers

5.1 Introduction

Ground source heat is a renewable source of energy stored in the subsurface. Its utility relies on the thermal gradient between a heat source or sink and the subsurface. As the subsurface has nearly constant temperatures below ca. 10 m, it can act as a heat source during winter and a sink during summer. This makes ground source heat a suitable choice for space heating and cooling. A borehole heat exchanger (BHE) is a common method of exchanging energy with the subsurface.

Performance of BHEs partly depends on the effective thermal conductivity of the ground. Effective thermal conductivity is the thermal conductivity of an equivalent homogenous isotropic material which transfers heat at the same rate. A potential key factor in determining effective thermal conductivity is the groundwater velocity. Groundwater flow can significantly enhance effective thermal conductivity of the ground (Chiasson et al. 2000; Sanner et al. 2000; Liebel 2012). Consequently it can also have a significant impact on temperature distributions around boreholes and their performance (Gehlin and Hellström 2003; Diao et al. 2004; Dehkordi and Schincariol 2013). As groundwater flow enhances the ground effective thermal conductivity and heat transport, it can result in shorter BHEs and lower installation costs (Wang et al. 2009). Nordell et al. (1986) performed hydraulic and explosive fracturing in a pilot borehole field and estimated fracturing reduced system installation costs by 10-15%. Modelling of flow and temperature profiles in a borehole during drilling by Fomin et al. (2005) shows reduced borehole temperature at the interception of fractures with the borehole where the fluid leaks out.

The standard thermal response test (TRT) (Austin 1998, Gehlin 2002) is a method to estimate the ground apparent thermal conductivity. In a TRT, the BHE is connected to a heating source while the temperature of a circulating heat carrier fluid is measured.

Increased apparent thermal conductivities due to groundwater flow in homogenous porous media (Chiasson et al. 2000; Sanner et al. 2000; Lee and Lam 2009) and non-homogeneous media (Chiasson et al. 2000, Gehlin and Hellström 2003, Liebel et al. 2012) have been reported. In an experiment by Lim et al. (2007), natural groundwater flow in a fractured granitic aquifer was detected during a TRT. They report higher thermal conductivity and reduced borehole resistance in two different regions of the test well interpreted with groundwater flow. Thermal response testing in a fractured hard rock aquifer by Liebel et al. (2012) shows an 11% increase in the ground effective thermal conductivity under induced groundwater flow conditions compared to the no groundwater flow case. This level of increase was related to only one major horizontal fracture with additional enhancement expected under higher groundwater flows.

This study intends to determine how hydraulically conductive inhomogeneities effect BHE performance and impact. Thus both changes in loop fluid temperatures and the transport of thermal plumes are studied. The inhomogeneity features in this study are in form of fractures. Therefore this work exhibits the effect of heterogeneity at its extreme as the discontinuity in the fractured rock makes highly heterogeneous and potentially anisotropic. Attributes of the fracture(s), i.e. aperture, number (and frequency), orientation, and distance from the borehole (for vertical fractures) or depth of the fracture (for horizontal fractures) are examined to define the main factors influencing BHEs in the long-term. Moreover a TRT is simulated to inspect its ability to detect nearby inhomogeneities.

5.2 Data and methods

The modelled thermal load is defined as a sinusoid of specific heat extraction peaking at 75 W/m; the operational time is 9 months followed by a 3-month period of inactiveness (Figure 5.1). The same cycle is repeated over the entire 25 years simulation time. Properties of the BHE are presented in Table 5.1.

A model with no fractures in which heat transport is essentially only through conduction is used as a basis for comparison against scenarios with discrete advection. The rock type simulated in this study is a crystalline rock of low porosity (2.5%) and hydraulic conductivity (10^{-12} m/s) which results in negligible advective transport within the rock matrix. Hydrogeological and thermal properties of the ground are tabulated in Table 5.1 and follow from Hellström (1991), and Domenico and Schwartz (1998).

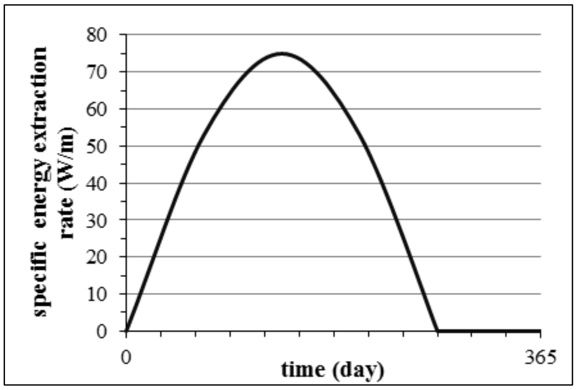

Figure 5.1 Annual specific energy extraction rate function.

It is generally a complex task to measure the hydraulic gradient in fractured rock media; based on common values as reported by Åberg and Johansson (1998), a gradient of 0.01 is assigned here. However, fracture properties such as orientation, aperture and frequency, are often simpler to measure though fracture mapping. Fractures can be categorized in six classes based on their aperture (Barton 1973, Gehlin and Hellström 2003). These categories – with modifications in category names – are formulated in Table 5.2. Apertures of 0.1 mm, 1 mm and 10 mm are assigned to the fractures modelled here, which places them in tight, open and wide categories correspondingly. As the BHEs simulated in this study are vertical, in accordance with common installation practice, for simplicity the fractures are modelled as either vertical or horizontal. Vertical fractures allow for interconnecting networks and varying distances from the BHE. However, horizontal (i.e. parallel) fractures allow for the depth of intersection with the BHE to be accounted for. Thus, the major properties of a fracture (network) interacting with a BHE are examined here at their end members.

Table 5.1 Borehole heat exchanger and ground properties.

Parameter	**Value**	**Unit**
Borehole thermal resistance	0.08	m·s·K/J
Internal borehole thermal resistance	0.3	m·s·K/J
Dynamic Viscosity of Refrigerant	0.052	kg/m/s
Thermal Conductivity of Refrigerant	0.415	J/m/s/K
Heat Capacity of Refrigerant	4050	J/kg/K
Density of Refrigerant	1045	kg/m^3
Flow Discharge of Refrigerant	20	m^3/d
Borehole Diameter	0.1524	m
Pipe Distance (centre to centre)	0.075	m
Pipe Outer Diameter	0.0381	m
Pipe Wall Thickness	0.0035	m
Depth	100	m
Background temperature	10	°C
Porosity of rock	0.025	-
Hydraulic conductivity of rock	10^{-12}	m/s
Volumetric heat capacity of groundwater	4.2×10^6	J/m^3/K
Thermal conductivity of groundwater	0.65	J/m/s/K
Volumetric heat capacity of rock	2.25×10^6	J/m^3/K
Thermal conductivity of rock	4.5	J/m/s/K

Table 5.2 Classification of fractures based on their openness (modified after Barton 1973, Gehlin and Hellström 2003).

Aperture (mm)	**Category**
<0.1	very tight
0.1-0.25	tight
0.25-0.5	partly open
0.5-2.5	open
2.5-10.0	very open
10.0<	wide

Under the assumption of a laminar flow of an incompressible fluid along the axis of a cylindrical tube, the Hagen–Poiseuille equation related the head drop (i) to the flow rate (*Q*):

$$Q = \frac{\pi r^4}{8\mu} i \tag{5.1}$$

where *r* is the radius of the cylinder, and μ is the viscosity of the fluid. The Hagen–Poiseuille law relates the velocity and flow in a fracture to its width and the drop in fluid pressure. Assuming laminar flow between two parallel plates with smooth surfaces, the flow can be calculated from the cubic-law:

$$Q = \frac{\rho g}{12\mu} d^3 H i \tag{5.2}$$

where *d* is the fracture width and *H* is the fracture height. The cubic-law, Equation 5.2, shows that fracture width is cubically related to the fracture flow while i is linearly related to it. Therefore fracture aperture plays a more important role in determining flow than hydraulic gradient. Corresponding hydraulic conductivity of the fracture (*K*) is calculated from Equation 5.3:

$$K = \frac{\rho g}{12\mu} d^2 \tag{5.3}$$

5.2.1 Model validation

The borehole is represented by a finite line in the node where the BHE solution is applied. The solution used in this study, is the Eskilson and Claesson's (1988) analytical solution, improved and described as robust and accurate, especially as steady state is approached, by Diersch et al. (2010, 2011a, 2011b). The improvements include thermal resistance relationships and direct, non-iterative coupling to the three dimensional (3D) discretized matrices of the porous media. As the BHE solution is represented and coupled with the rest of the model by a one dimensional (1D) element, the temperatures in close proximity to the BHE may not match the actual temperature distribution. Therefore it is validated here against a fully discretized 3D model (FD3DM). The FD3DM approach is more precise as all BHE elements (i.e. heat carrier fluid inside the pipe, pipe walls and grout) are discretized.

The validation is conducted for: (a) no fracture model where heat transport is primarily through conduction, (b) vertical fracture model with a 1 m separation between BHE and fracture, and (c) horizontal fracture model with a horizontal fracture intersecting the BHE at a 50 m depth. For simplicity a constant inlet temperature of 0 °C is assumed. The resultant outlet temperatures, from the FD3DM and 1D representation of the BHE after 365 days, are compared in Table 5.3. Mesh convergence studies are done in proximity of the discrete feature elements (DFEs), horizontally and vertically. Final element size is approximately 0.25 m near the DFEs.

Table 5.3 Validation of the outlet temperatures from FD3DM and 1D borehole models.

Case	**Outlet temperature (°C) after 1 year**	
	FD3DM	**1D**
No fracture (a)	3.4	3.3
Vertical fracture at 1 m distance (b)	3.9	3.8
Horizontal fracture at 50 m depth (c)	3.4	3.3

5.2.2 Thermal response testing

A thermal response test (TRT) is an in-situ method of measuring the apparent thermal conductivity of the ground. During a TRT, heat is continuously injected to (or extracted from) the ground at a constant rate. The temperature of the heat carrier fluid circulating in the loop is measured throughout the test. The commonly recommended duration of a thermal response test is around 50 hours or more (Skouby 1998; Spilker 1998; Spitler et al. 1999; Austin et al. 2000). In this study a TRT lasting 72 hours is simulated. However, compared to the life cycle of a typical BHE the TRT represents a very limited view into its operational characteristics and impact zone.

5.3 Results and Discussion

5.3.1 Homogeneous no-fracture model

In order to determine the effect fractures have, a conduction-only model is simulated (Figure 5.2). In the conduction-only case it takes about 15 years for the system to reach a quasi-steady state, with the minimum fluid temperature further reducing by only 0.2 °C after 25 years.

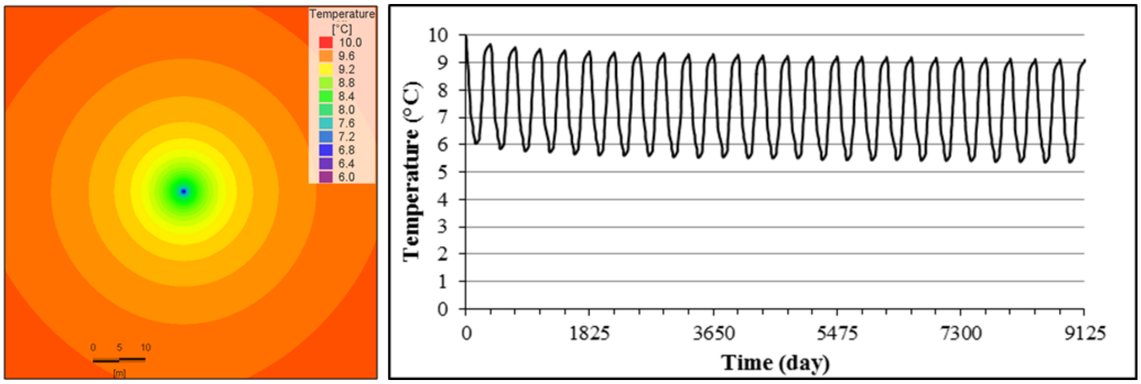

Figure 5.2 Temperature distribution around the BHE, 25th year (left) and fluid temperature (right) in the reference conduction model.

5.3.2 Heterogeneous models with fractures

Fracture frequency, aperture and connectivity are factors that control the hydraulic conductivity of the fractured rock and thus groundwater flow. In this study, discrete fractures are modelled in a local-scale context. Therefore, all fractures are assigned equal hydraulic gradient and the flux is defined by gradient and aperture. At the local scale of the model, flow in the fractures is assumed to be independent of fracture connectivity which is more relevant at the regional scale. All the following modelled (both vertical and horizontal) fractures are 1 mm open. For vertical fractures, their distance from the BHE, aperture and configuration, including number (and frequency) and orientation (strike) of fractures will be studied. For horizontal fractures, depth and width at which they intersect with the BHE will be considered. Length of the intersection can depend on both fracture aperture and number of fractures (or their frequency) which are separately examined.

5.3.2.1 Vertical fractures

Loop temperatures in the homogenous no-fracture model are compared with those of three equally heterogeneous models with one vertical fracture. The borehole is moved relative to the vertical fracture at distances of 1 m, 5 m and 10 m. As the BHE gets closer to the fracture, the thermal plume becomes more dispersed downgradient along the fracture (Figure 5.3). Looking at the minimum loop temperatures, performance efficiency seems very sensitive to the distance between the BHE and the fracture (Figure 5.4). Table 5.4 shows that a single fracture, near the BHE (1 m, 5 m and 10 m) can improve the fluid temperature (25%, 11% and 6% respectively). The sensitivity diminishes as the BHE gets farther from the fracture. Moreover closer fractures (e.g. 1 m) have an earlier impact on system efficiency (1st year in this case), whereas the impact from farther settings (e.g. 10 m) is more delayed (Figure 5.4 and Table 5.4). Table 5.4 contains maximum recorded drops in loop temperatures (occurs at the peak heat extraction times) from the initial 10 °C in the 1st and 25th years. These temperatures are then used to quantify the stabilization and performance of each BHE model. As the peaks in Figure 5.4 show the recovery of loop temperatures is less sensitive to the fracture distance and more linearly related to it.

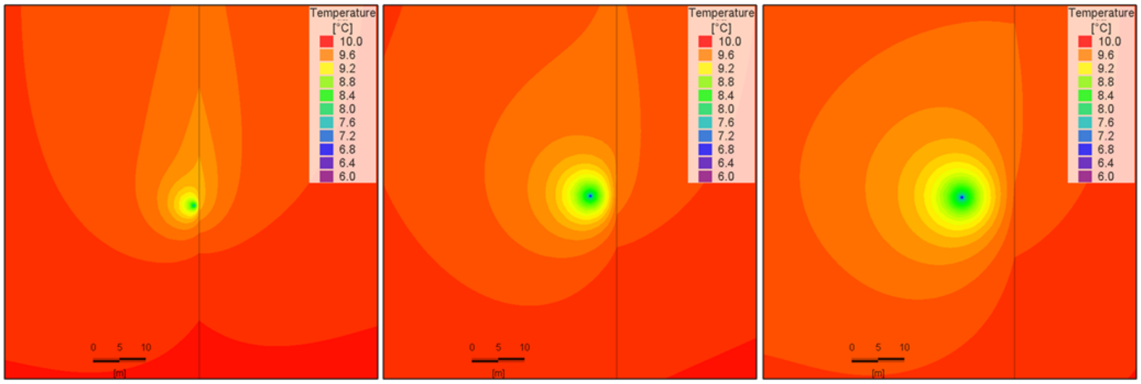

Figure 5.3 Thermal plume with a 1 mm open vertical fracture at 1 m (left), 5 m (centre) and 10 m (right) from the BHE.

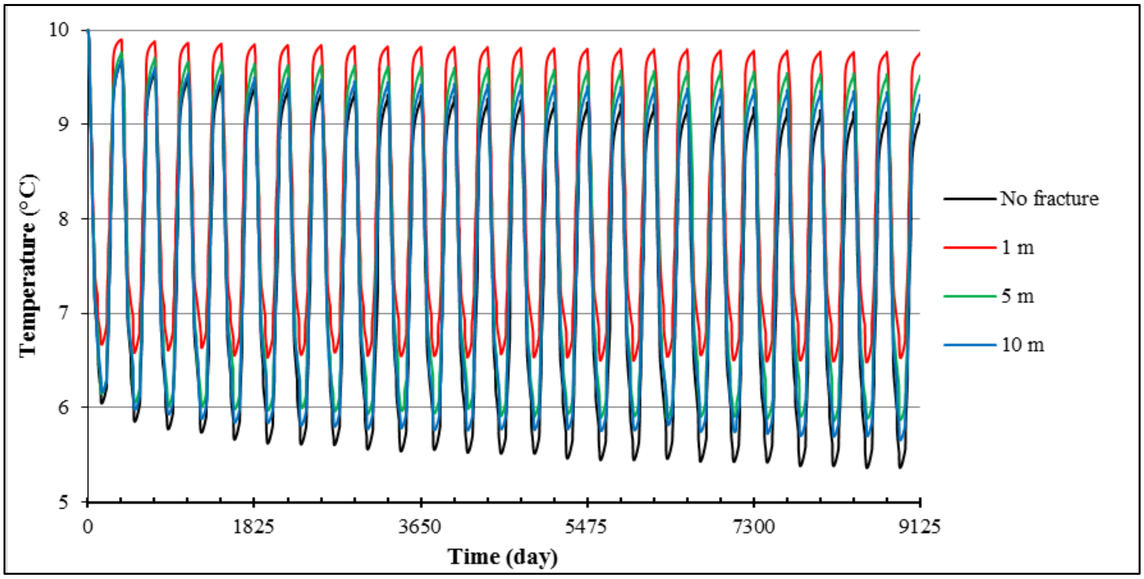

Figure 5.4 BHE fluid temperatures in models with a 1 mm open fracture at 1 m, 5 m and 10 m distances from the borehole compared to a homogeneous model with no fracture.

Table 5.4 Comparison of loop temperatures against fracture distance (1 mm aperture).

Heterogeneity conditions	**Maximum drop in fluid temperature (°C)**			
	1st year	**25th year**	**1st year/25th year***	**Ratio to the no-fracture case in 25th year****
Fracture at 1 m	3.33	3.47	96%	75%
Fracture at 5 m	3.84	4.13	93%	89%
Fracture at 10 m	3.84	4.35	88%	94%
No fracture	3.95	4.64	85%	100%

* Indication of how quick the loop temperatures stabilize. Higher is better.
** Indication of how much the loop temperatures improve. Lower is better.

Different apertures: tight (0.1 mm), open (1 mm) and wide (10 mm), at a 5 m distance from the BHE are modelled. Temperatures of the ground and loop fluid show that a tight fracture has a negligible effect on temperature distribution around the BHE (Figure 5.5 *left*). Fractures with a 1 mm and 10 mm aperture considerably reshape the plume and effectively recover the ground temperatures (increase the temperature gradient) in the distance between the BHE and the fracture (Figure 5.5 *middle*, *right*).

They also confine the thermal plume such that temperature changes beyond the fracture setting are insignificant. For the 10 mm wide fracture the ambient ground temperature field is negligibly impacted. The fracture generally causes downgradient extension of the thermal plume (Figure 5.2 *middle*). Comparing the temperature disturbances along the fracture (Figure 5.5 *right*) with the conduction only case (Figure 5.2 *left*) illustrates how fractures can isolate BHE temperature disturbances. The large extension of impact along fracture planes points to the need for evaluating the effect of any large upgradient geothermal systems located in fractured rock terrains. While increase in fracture aperture, from tight (0.1 mm) to open (1 mm), has a noticeable impact on loop temperatures and stabilization time, further widening, from open (1 mm) to wide (10 mm), has a relatively subtle effect (Figure 5.6 and Table 5.5). Table 5.5, weighs the effect of fracture aperture on steadying and enhancing the short-term and long-term performance of the modeled BHEs – in the same way as Table 5.4.

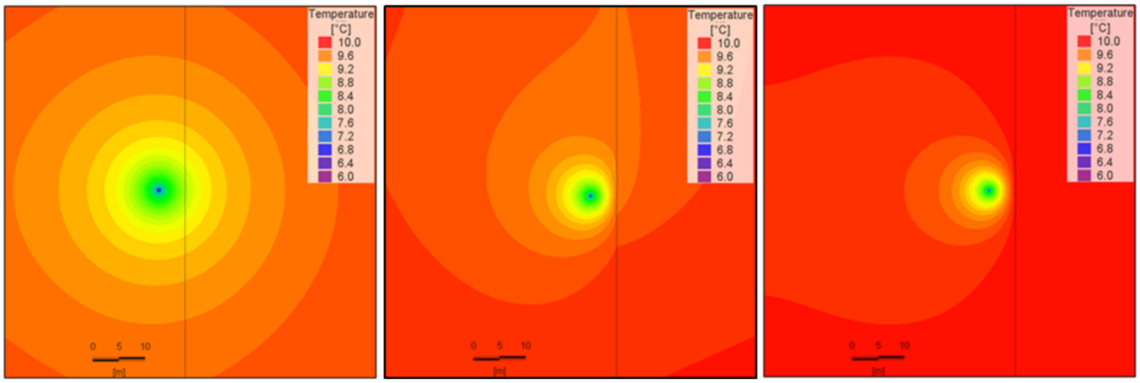

Figure 5.5 Thermal plume with a vertical fracture at 5 m from the BHE: 0.1 mm (left), 1 mm (centre) and 10 mm (right) fracture apertures.

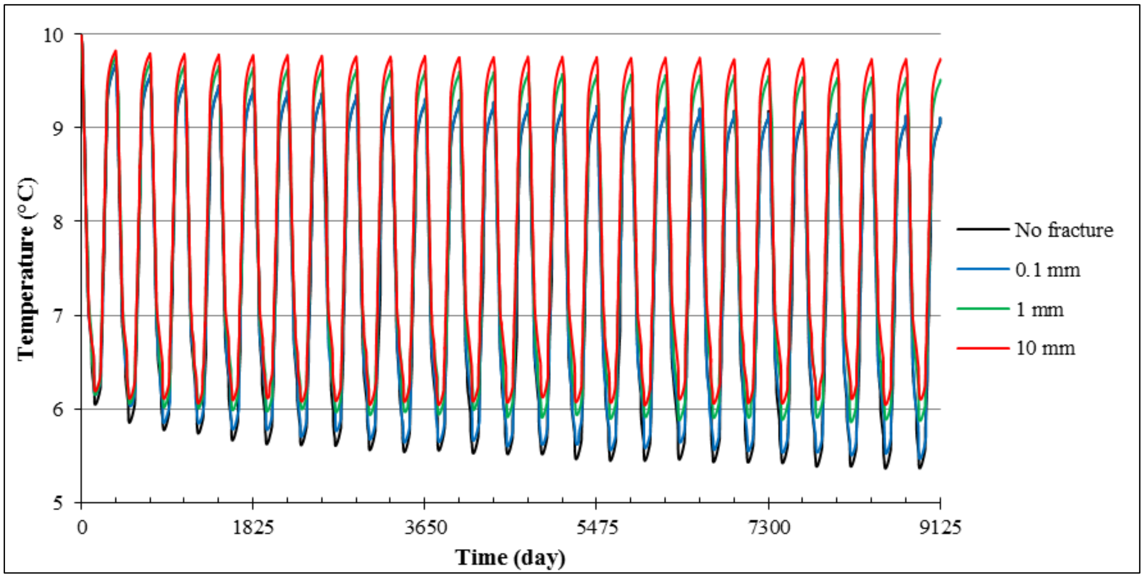

Figure 5.6 BHE fluid temperatures in models with 0.1 mm, 1 mm and 10 mm fracture apertures at 5 m distance from the borehole compared to a homogeneous model with no fracture.

Table 5.5 Comparison of loop temperatures against fracture aperture (5 m distance).

Heterogeneity conditions	**Maximum drop in fluid temperature (°C)**			
	1st year	**25th year**	**1st year/25th year***	**Ratio to the no-fracture case in 25th year****
0.1 mm fracture	3.85	4.53	85%	98%
1 mm fracture	3.85	4.13	93%	89%
10 mm fracture	3.81	3.90	97%	84%
No fracture	3.95	4.64	85%	100%

* Indication of how quick the loop temperatures stabilize. Higher is better.
** Indication of how much the loop temperatures improve. Lower is better.

Simulating parallel fractures on the same side of the borehole at 1 m and 5 m distance from the borehole shows that the closest feature has the most significant influence on the BHE performance. Fluid temperatures with two fractures are almost equal to those with one fracture at 1 m (Figure 5.7 *right*). The spatial distribution of temperatures in the plume's centre, and therefore the fluid temperature, is dominated by the closest fracture. However the more distant fracture(s) further limits the plume size and reduces thermal disturbance perpendicular to the fracture (Figure 5.7 *left*). This may explain why increases in fracture aperture does not steadily raise the system efficiency but limits the plume size as a thicker fracture can be discretized as a number of thinner fractures in immediate vicinity of each other.

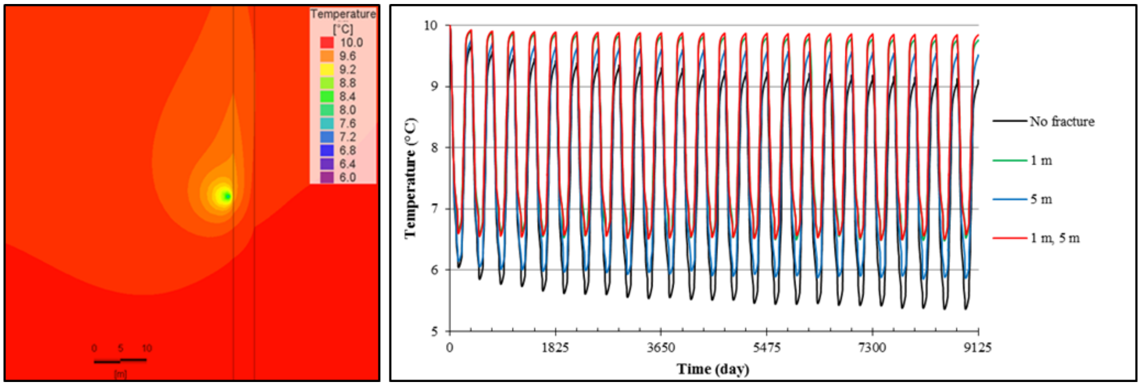

Figure 5.7 Temperature distribution around the BHE with two vertical fractures at 1 m and 5 m distances, 25th year (left) and fluid temperature with fractures at 1 m, 5 m, and 1 m and 5 m (right).

Thermal plumes in Figure 5.8 show that as the number of fractures around the BHE increases (all at the same distance, 5 m) the thermally disturbed zone becomes more confined to the space between the fractures. The magnitude of temperature changes from the initial background value also lessens in both the upgradient and downgradient directions. Comparison between two parallel and perpendicular fractures indicates that parallel structures more effectively retain the ground temperatures closer to the its initial background state as the two fractures do not interconnect. While a single fracture improves the loop fluid temperatures by 0.55 °C, further increases to four perpendicular fractures only increases fluid temperatures to 0.7 °C, i.e. ca. 25% °C added enhancement caused by introducing three more fractures (Figure 5.9). Thus based on the fracture aperture and distance from the BHE, one fracture can be identified as the major feature affecting the loop temperatures; while other fractures may influence the thermal plume transport their effect on performance is comparatively minor. The loop temperature shown in Figure 5.9, also confirm that parallel fractures enhance the performance efficiency of the system more that interconnecting ones.

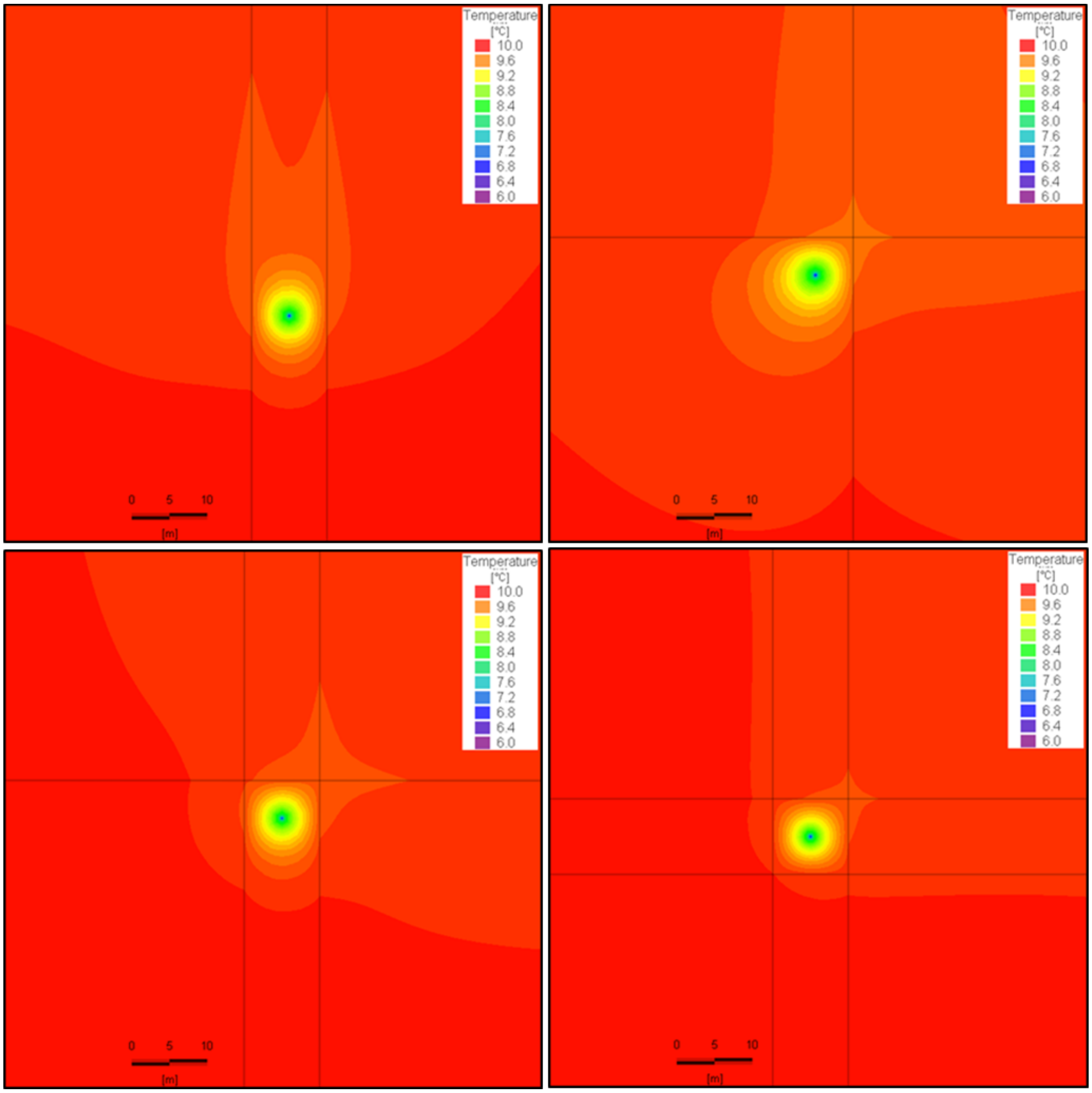

Figure 5.8 Thermal plume with 1 mm open vertical fractures at 5 m: two parallel (top-left), two perpendicular (top-right), three crossing at 90 ° (bottom-left) four crossing at 90 ° (bottom-right).

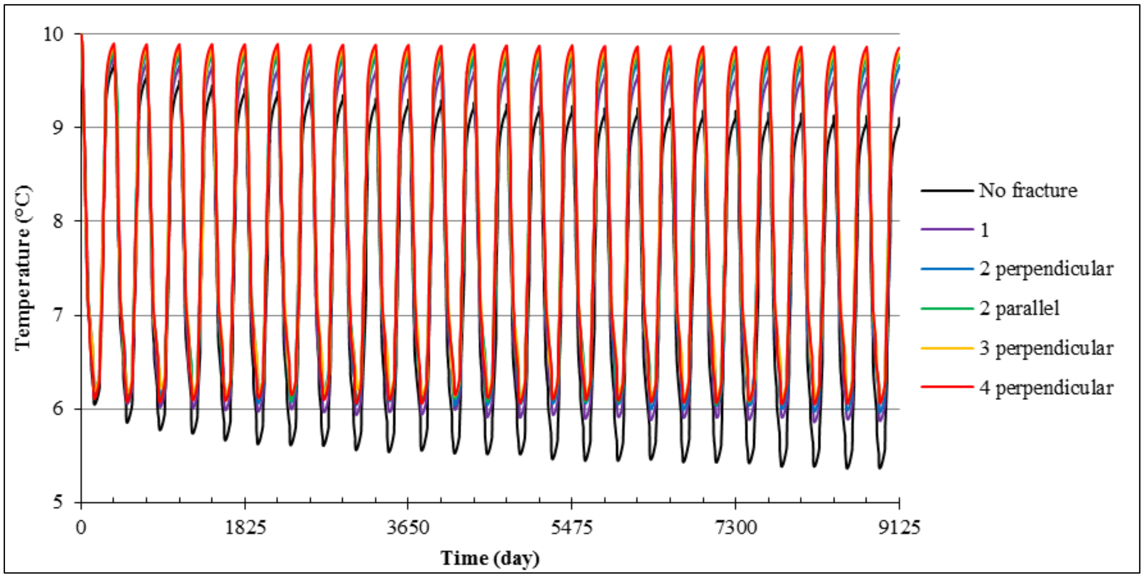

Figure 5.9 BHE fluid temperatures in models with single and multiple open fractures (1 mm) at 5 m distance from the borehole compared to a homogeneous model with no fracture.

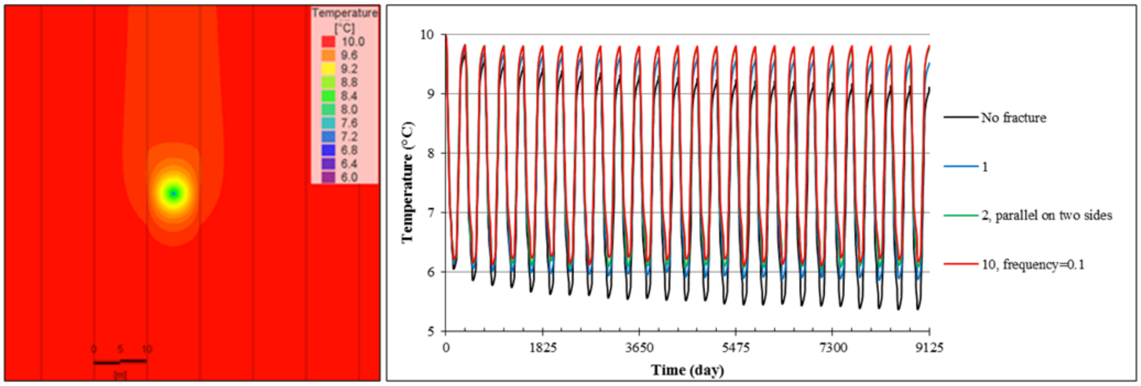

Figure 5.10 Temperature distribution around a BHE with 10 parallel vertical fractures at 10 m spacing (frequency=0.1), BHE distance from nearest fracture=5 m, 25th year (left) and corresponding fluid temperature, plus fluid temperatures from 2 parallel fractures and 1 fracture each 5 m from the BHE and no fracture (right).

To extend the study to beyond a set of two fractures the BHE is placed in fracture zone with frequency of 0.1, meaning one fracture every 10 m. Similar to the previous findings, but more effectively, the thermally disturbed zone is confined between the two closest fractures (Figure 5.10 *left*) and the performance enhancement by additional fractures is insignificant relative to one fracture (Figure 5.10 *right*).

Given the influence that open (or wide) vertical fractures in vicinity of a BHE can have on confining the thermal plume, reducing thermal disturbance, and enhancing system efficiency, their role in reducing thermal interference between BHEs is investigated. A vertical open fracture (aperture 1 mm) passing between two BHEs lessens the thermal interaction by transporting the heat and recovering the temperatures between them, as if they are located at larger distance that what they actually are (Figure 5.11). Fluid temperatures confirm the consequent positive impact on system performance, with a single fracture between BHEs resulting in ca. 1 °C increase in fluid temperatures, i.e. 20% decrease in temperature drop (Figure 5.12).

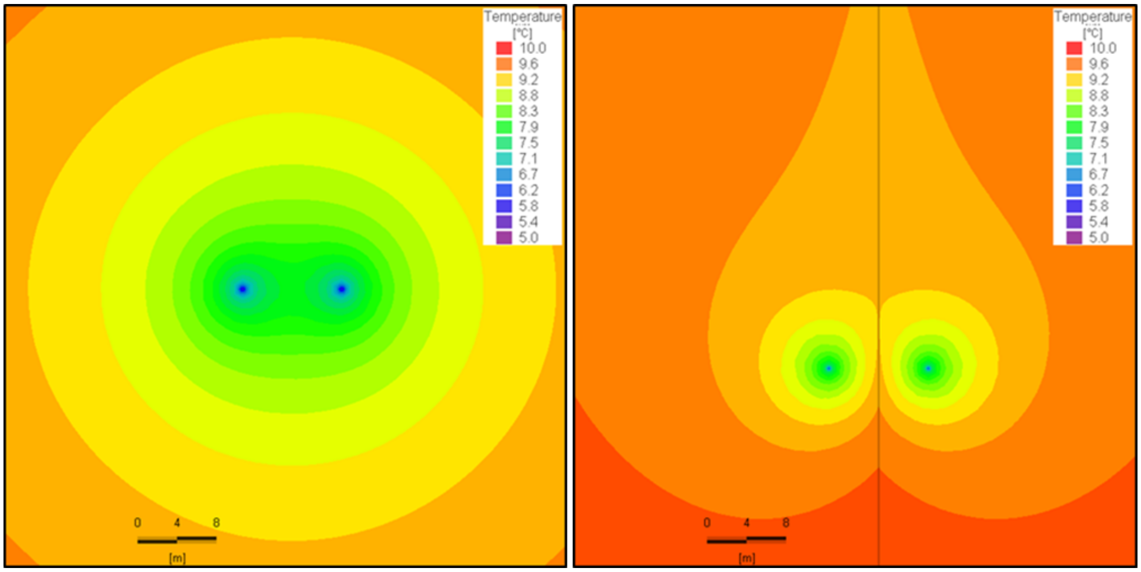

Figure 5.11 Thermal plume from 2 BHEs 10 m apart, in homogeneous media (left) and with an open (1 mm) vertical fracture at 5 m from each BHE (right) in the 25th heating cycle.

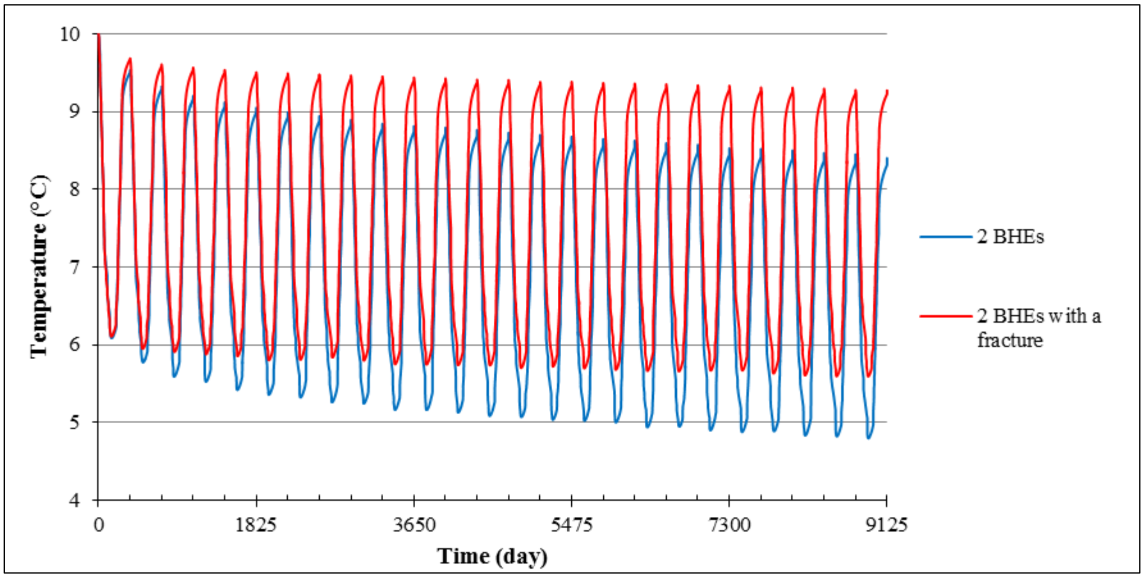

Figure 5.12 Fluid temperatures in 2 BHEs at 10 m separation with no fracture compared to a case in which a vertical open (1 mm) fracture is located in the middle of the BHEs at 5 m distance from each.

5.3.2.2 Horizontal fractures

While vertical fractures can have different strikes and may or may not intersect a BHE, any horizontal fracture that intersects the borehole will influences its performance, given the assumed horizontal groundwater flow field. This makes analysing them simpler than vertical features (depth vs. distance and configuration). As with the modelled vertical fractures, an aperture of 1 mm is assumed for the horizontal fractures.

Intersecting the BHE with a horizontal fracture at a depth of 50 m shows a significant alteration in temperatures at the fracture depth (Figure 5.13 *middle*). At 5 m above/below the fracture depth, the plume is impacted regionally but temperatures around the BHE follow a circular pattern associated with conductive-dominated heat transport (Figure 5.13 *left*, *right*). This clearly illustrates that the fracture thermal influence zone extends well beyond its thickness. Loop temperatures (Figure 5.14) show only a subtle variation compared to the no-fracture case.

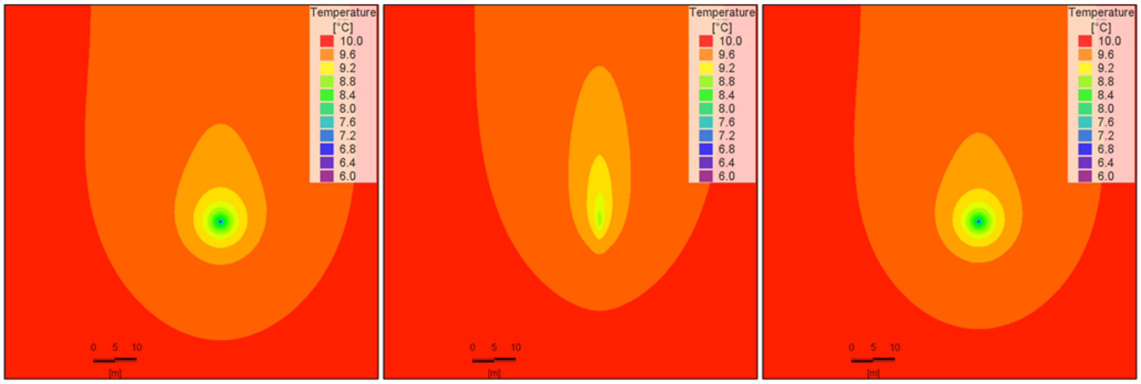

Figure 5.13 Thermal plume with a 50 m deep, 1 mm open horizontal fracture at 45 m (left), 50 m (centre) and 55 m (right) from the surface.

Horizontal fractures intersecting the BHE at various depths are modelled to see if depth to the fracture is an important attribute. The results show that the loop temperatures during operation are negligibly affected by the fracture depth (Figure 5.14). While loop temperatures are virtually not affected by fracture depth during BHE operation, they are marginally affected during thermal recovery. The thermal recovery period is the time when the system is not operating and ground temperatures return to their initial values, i.e. background temperature. The shallower fractures are marginally more effective at enhancing the loop temperatures. Compared to the no-fracture model, one horizontal fracture has caused approximately a minor 0.2 °C enhancement in fluid temperature at its peak.

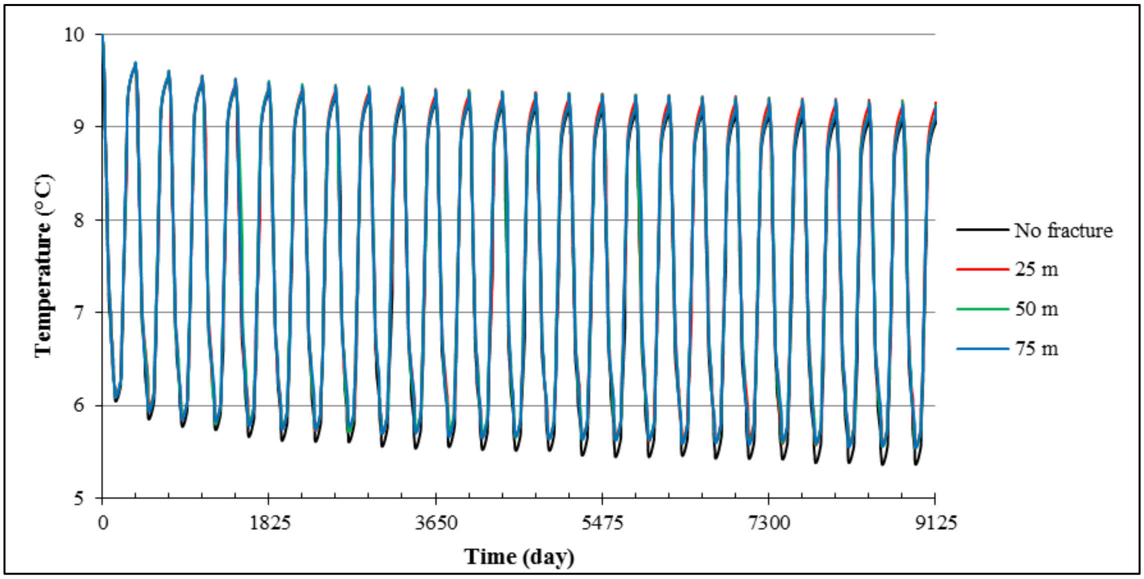

Figure 5.14 BHE fluid temperatures with a horizontal open (1 mm) fracture intersecting the borehole at 25 m, 50 m and 75 m depths, and no-fracture model.

In order to study the effect of fracture openness on fluid temperature locally, the loop temperature profile is plotted against the borehole depth (Figure 5.15). Increasing the fracture opening to 10 mm causes a slightly more abrupt change in the loop temperature at a depth of 50 m. Moreover, increasing the fracture aperture from 1 mm to 10 mm leads to about the same rise in loop temperatures that an increase from 0.1 mm to 1 mm does. In turn 10 fractures with 1 mm opening have more influence on the temperature profile than a single 10 mm fracture. This is despite the fact that according to the cubic-law a 10 mm fracture conveys more flux than 10×1 mm ones. The grout temperatures more clearly show the temperature disturbances at depths above and below the fracture(s) (Figure 5.15). Similarly loop temperature versus time show that between fracture sets with the same total aperture (10 mm vs. 10×1 mm) the one with higher frequency affects the loop temperatures significantly more; the difference is obvious from the first year (Figure 5.16). These results suggest that in a horizontal fracture set, the number of fractures (frequency) is more important than fracture aperture for enhancing the BHE efficiency. This can be explained by the extension of the fracture's thermal effect zone further than its opening (Figure 5.13). This effect naturally intensifies as more fractures are introduced.

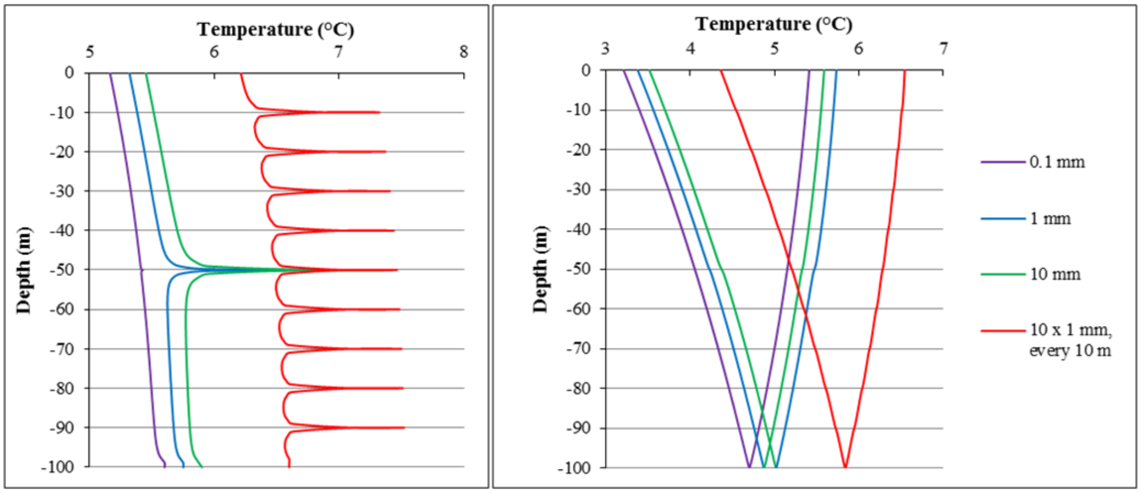

Figure 5.15 Minimum grout (left) and BHE fluid (right) temperatures in the 25th year with horizontal fractures of various apertures intersecting the borehole at 50 m depth, and 10×1 mm fractures at every 10 m.

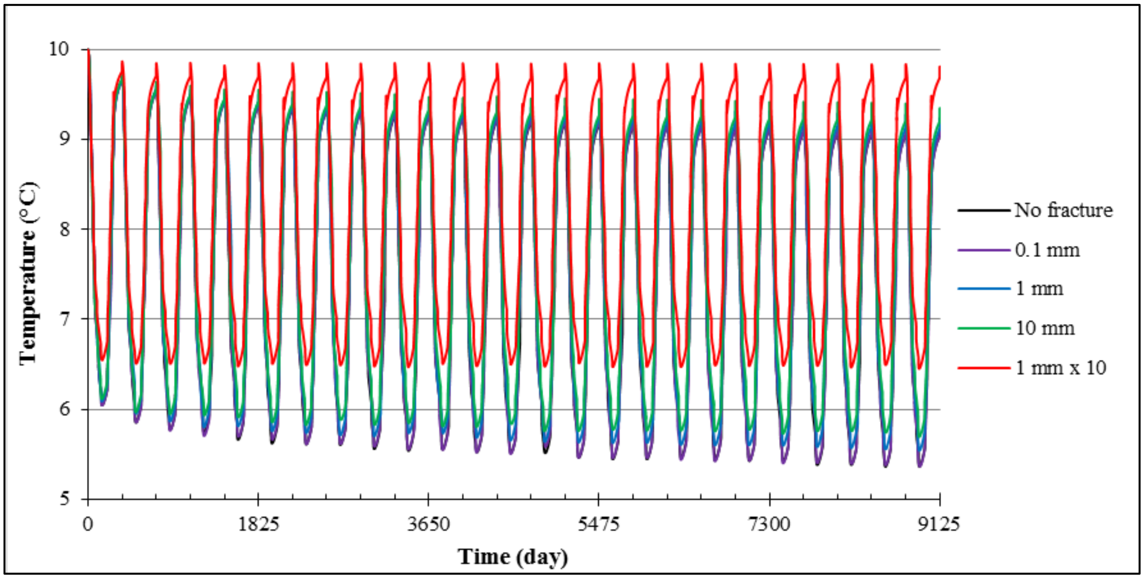

Figure 5.16 BHE fluid temperatures with horizontal fractures of various apertures intersecting the borehole at 50 m depths, and 10×1 mm fractures at every 10 m, compared to the no-fracture model.

5.3.3 Thermal response test simulation

The loop temperatures and impact zone of the TRT are simulated with the same BHE and ground properties as in Table 5.1. The loop fluid flow rate is 40 m^3/d producing a 50 W/m heat injection rate. Simulations are done for a homogenous situation as well as a case with some heterogeneity introduced. The homogenous model represents fracture-free bedrock while the heterogeneous model contains one vertical fracture at 5 m distance from the BHE.

The fluid temperatures show that the test does not identify a hydraulically and thermally conductive feature located 5 m away from the borehole due to its limited impact zone (Figure 5.17). The simulations therefore prove that a short-term standard TRT is not adequate for identifying inhomogeneities located at a 5 m distance from the borehole. However, as the earlier results showed in the long-term, fractures at such distance (5 m), and even further (10 m), can actually have an effect on BHE performance. Continuing the simulation beyond standard TRT times, shows that even after 30 days at 5 m away from the BHE, temperature differential is only 0.1 °C (Figure 5.18). This difference is nearly 0 °C after 5 days, being a rather long TRT.

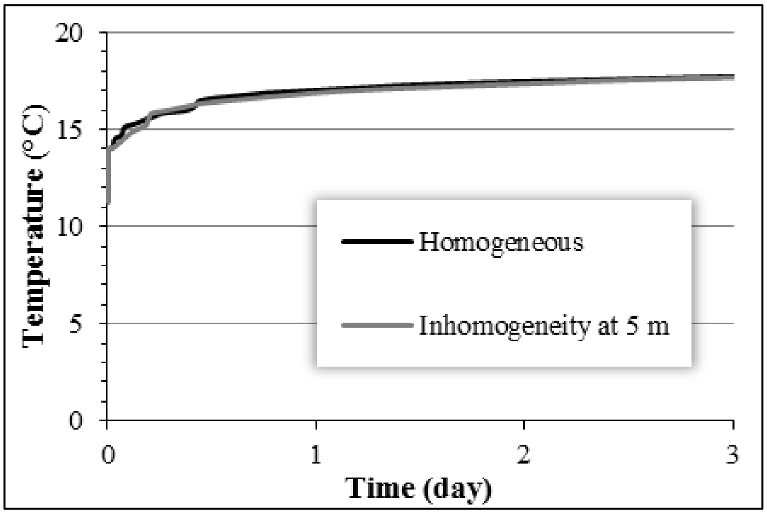

Figure 5.17 Simulation thermal response test fluid mean temperatures from homogeneous and inhomogeneous (a single vertical 1 mm open fracture at 5 m distance from the BHE) cases.

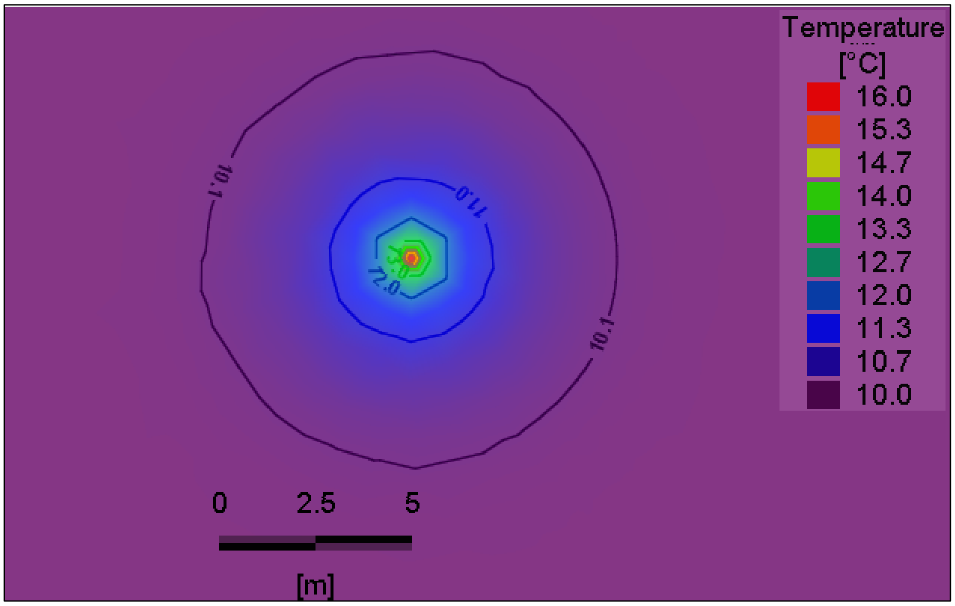

Figure 5.18 Temperature disturbance around a BHE in a homogeneous background as a result of a hypothetical TRT after 30 days. Temperature differential at 5 m from the BHE is only 0.1 °C.

5.4 Conclusions

The influence of fractures on BHEs is different based on their dip angle. In vertical fractures the distance from the borehole appears to be the most critical factor. Openness of the fracture is also important; a tight fracture will have a minor influence while a wide fracture has a significant effect. However, increasing the aperture from open (1 mm) to wide (10 mm) has a less significant influence than that from tight (0.1 mm) to open (1 mm). Multiple vertical fractures are most effective in improving the BHE performance if parallel and least effective when inter-crossing perpendicularly. Among multiple fractures the nearest hydraulically open fracture has the most influence on loop temperatures. Therefore, number or frequency of vertical fractures is of lower significance. The top ranked factors, distance between BHE and fracture, fracture aperture and fracture configuration (in that order) are all rather easily assessable through geological mapping and geophysical measurements.

The effect of horizontal fractures on the BHE temperatures is not sensitive to the fracture depth along the borehole. Number and frequency of horizontal fractures and their aperture are relevant factors as they increase the contact length between the BHE and the fracture. However, the number of fractures is more important than their openness since multiple fractures have a larger vertical impact zone than a single fracture with equivalent total opening. Fracture frequency along the BHE depth, and the less important fracture width, are measurable by borehole logging or less accurately through outcrop fracture mapping. As mentioned in ‘Data and methods’, these conclusions are based on the end member fracture orientations (vertical and horizontal) which while highly simplified, address the major properties of fracture networks. Further studies on more complex fracture networks including inclined fractures is in order.

Although the short-term thermal response test is an effective way for measuring the apparent thermal conductivity of the ground, it may not be adequate for evaluation of long-term performance of larger systems in highly heterogonous material like fractured rock. In such settings, measurements of rock thermal properties (even by sensors when primary heterogeneity is low) could be combined with other investigation techniques such as fracture mapping, or even borehole logging and geophysical methods, for detection of rock structures. These investigations can also aid locating the BHE(s) to increase efficiency and reduce interference.

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Chapter 6

6 Final statements

6.1 Conclusions

This study ultimately aimed at improving the sustainability of vertical closed loop borehole heat exchangers in interaction with groundwater flow. Reviewing the design methods and legislative environments, as the main mechanisms to guarantee a permissible and maintainable usage, shows that they are falling behind the current state of research as to when the effect of groundwater flow is no longer ignorable. The common practice in design of closed loop geothermal systems excludes the effect of groundwater advection-dispersion, even though there are analytical solutions and numerical flow-heat transport models available. The regulatory milieu can provide exact thresholds for groundwater flow rate, above which advection of groundwater must be integrated in the design procedure. This would especially be of concern where density of installations is high or when sensitive features, like protected groundwater areas and sensitive aquatic ecosystems are present.

Previous studies have shown that the recovery time – time for disturbed subsurface temperatures to return to their initial state – is equal to operation time for a single BHE and becomes greater for multiple BHEs. Simulations shown here confirmed this finding, and also found that after the BHE is shut down, the highest disturbances vanish rapidly, and as the temperatures get closer to background temperature, the rate of dissipation slows down. At far distances from the BHE, there might be a short delay sensing the shutdown during which the thermal plume boundary continues to grow.

Although various studies have determined the influence of groundwater flow on the apparent ground thermal conductivity and performance of BHEs, its relative importance compared to other factors (i.e. subsurface thermal conductivity, volumetric heat capacity, thermal dispersivity and porosity, grout thermal conductivity, background and loop inlet temperatures) had not been as well understood. Analysis shows that groundwater flux, at around 10^{-6} m/s and higher, is one of the top ranked factors influencing BHEs. The impact becomes noticeable at ca. 10^{-7} m/s during production; and ca. 10^{-8} m/s during recovery. Increases in groundwater flow rate reduce the time to reach steady-state conditions, for both ground and loop temperatures. Groundwater advection distinctly shortens the borehole thermal recovery time; factors which are conduction-related do not significantly affect the recovery time. Thermal plumes significantly change shape depending on the magnitude and direction of groundwater flow, and spread most in the downgradient direction. Thus, while TRTs are applicable in calculating the apparent thermal conductivity for single BHE designs, they are not appropriate when assessing the transport of thermal plumes, e.g. thermal interference in a multi-BHE system. With every order of magnitude increase in groundwater flux its effect on heat transport becomes progressively more important. Hydrodynamic thermal dispersivity is not of significance at low groundwater flow rates, but at higher fluxes, e.g. 10^{-6} m/s, it can become influential. Nonetheless, accurate estimations of thermal dispersivity in situ are usually not possible, which makes it of low priority in hydrogeological investigations to plan BHE installations.

Porosity by itself – i.e. under constant hydraulic gradient and conductivity – does not impact the advective heat transport. However, considering the natural link between porosity and hydraulic conductivity (and the consequent effect on hydraulic gradient) it may affect the groundwater flux which controls the heat transport by advection. At flow rates below 10^{-7} m/s, where advection is small, these relations can often be safely ignored. Porosity affects the bulk thermal properties; due to the inferior thermal diffusivity of water compared to geological media, non-porous materials conduct the heat more efficiently than porous materials (note that porous media are more hydraulically permeable).

Thermal conductivity of the ground greatly affects its diffusivity and therefore the efficiency of BHEs. Tripling the thermal conductivity of the ground solids (nearly tripling its bulk thermal conductivity), doubles the long-term average specific heat extraction rate. As higher ground thermal conductivity improves the heat transport it causes regionally larger plumes; however, the reduced temperature gradients cause less temperature disturbances locally near the BHE. Thermal conductivity of the grout has a similar impact on the performance of BHEs. Although the grout volume is limited compared to the surrounding ground, it is important in the heat exchange due to its role in determining borehole thermal resistance. Even so, proper siting of a BHE would have a superiorly favourable impact on its thermal efficiency; the results show only a 10% improvement in specific heat extraction rate when switching to a thermally enhanced grout from one with poor thermal conductivity. Therefore other properties of the grout, e.g. viscosity and seal, should also be considered when choosing an ideal grout. Although volumetric heat capacity of the geological material can often be considered constant, varying it in a somewhat wide range did not prove it to be an important parameter affecting BHEs. Opposite to ground thermal conductivity (as in thermal diffusivity), its volumetric heat capacity has an inverse relationship with system performance and plume size.

One of the most important aspects governing the performance of BHEs is the temperature gradient between the loop and ground, i.e. fluid temperature and background temperature. A 2.5 °C change in background temperature corresponds to up to a 30% variation in heat extraction rates. Thus, accurate estimation of ground temperatures is essential for a correct design. This is especially important since ground temperatures are subject to variations caused by change in land-use or by temperature disturbances from adjacent BHE systems. Loop temperatures, on the other hand, are regulated by weather conditions and energy demand. During extreme cold and hot weather periods, where heat pump COP drops, the temperature gradient between BHE and background rises which enhances the heat exchange. Theoretically, freezing the ground can improve the performance of a BHE due to higher thermal diffusivity of ice than water, and storage of energy as latent heat while ground temperatures remain constant, i.e. 0 °C. Energy extraction rate, i.e. loop temperature, does affect the thermal recovery time but its extent is rather small.

In addition to the magnitude of energy load, its pattern is also essential in defining the long-term efficiency of BHE(s), especially in multi-borehole systems. With either heating or cooling load being dominant, unbalanced load, loop and ground temperatures are sensitive to the number of BHEs and choice of array type. As the number of BHEs increases or as a line array is reformed to a square array, system performance reduces while its impact grows. Being a major design factor, separation between the boreholes in an array plays an important role in their long-term thermal sustainability. Increases in the number of BHEs or decreases in their separation, substantially prolong the time to approach quasi-steady state. The significance of groundwater flow impact becomes greater on larger BHE arrays with an unbalanced energy load. The thermal interference between the BHEs caused by groundwater flow is potentially greater in line arrays than square arrays – under the worst case scenario of flow parallel to the array. Therefore, a more confident design, but not necessarily more efficient, can be done with a square array when groundwater flow direction is unknown or varies temporally and spatially.

When the energy load is balanced, i.e. heating and cooling loads are equal, system thermal performance is insensitive to array shape and number of BHEs in the array. Borehole spacing and groundwater flow affect the loop temperatures and resulted thermal plume; however, the effect remains constant in the long-term. Despite the BTES systems essentially having balanced energy loads in the subsurface part, their interaction with groundwater flow differs from that of ordinary multi-BHE systems. The heat exchange by conduction is efficient in BTES systems, due to storage of large amounts of energy and formation of high temperature gradients between BHEs and surrounding ground during the extraction phase. Groundwater flow not only causes introduction of larger amounts of heat to the subsurface, i.e. higher impact, it also lessens the energy extraction rate, i.e. lower efficiency.

Similar to homogenous hydraulic features, hydraulic non-homogeneities can also affect the borehole temperatures. In fractured rock, the fractures interact with the BHE based on their properties and location relative to borehole. Generally, vertical features tend to be affecting vertical BHEs more than horizontal ones. This, however, greatly depends on the distance between vertical fractures from the borehole followed by their aperture. According to the model simulations in this study, vertical fractures with ≥1 mm aperture up to 10 m away from the BHE can affect the loop and ground temperatures. When the BHE is surrounded by multiple fractures, which is normally the case, one fracture is responsible for the most influence on loop temperatures. This fracture can be designated by its openness and location relative to the borehole. Impact of additional fractures becomes progressively less. Similarly the temperatures in vicinity of the BHE are mostly affected by one major fracture. At the regional scale, additional fractures can be influential forming the thermal plume. However, in the same family of fractures (i.e. fractures with the same orientation) the closest ones interposed between the BHE and further fractures are of highest importance. Thus, the frequency of fractures in each set is of lesser importance. All these attributes, i.e. position relative to the borehole, aperture and configuration, are measurable through fracture mapping or geophysical methods.

Frequency and openness of horizontal fractures intercrossing with a BHE are principal factors in the assessment of groundwater flow impact on loop performance. However, fracture frequency is more effective because the thermal impact zone of each fracture extends beyond its aperture. In this regard, fracture openness ranks next. Although there are fewer principal factors to concern when dealing with horizontal fractures, an accurate quantification of them may be more difficult than vertical fractures. These characteristics can be measured by techniques such as fracture mapping and borehole logging. Location of fracture relative to the borehole, i.e. fracture depth, is unimportant in determining the impact on loop performance.

Thermal response testing is an applicable method for measuring the apparent thermal conductivity of the ground, which includes the effect of groundwater advection as well as thermal and hydraulic inhomogeneity. The limited temporal and spatial extent of a TRT compared to real BHE operation, can restrict its effectiveness in extremely heterogeneous environments, such as fractured crystalline rock. The effect of horizontal fractures intercrossing the borehole on TRT results is regardless of the test duration; however, the effect of vertical fractures depends on the test properties, e.g. heat input rate and duration. Therefore, a short-term standard TRT can be combined with the knowledge about vertical heterogeneity features, to provide better results. Alternatively, when the primary heterogeneity is low, point measurements of thermal conductivity can be processed concurrently with the information from site investigation techniques.

6.2 Future research recommendations

As per the aim of this study and the conclusions drawn, it is suggested that the legislation applied to geothermal heat pump systems adapt to the current scholarly advancements. This can be in the form of imposing thresholds on groundwater flow, above which groundwater shall not be ignored. Such integration could be eased by the research community through finding simply applicable methods such as flow-dependant design factors or monograms. Likewise, the developments in computation techniques such as flow-heat coupled numerical models and more recent analytical solutions should be implemented in the process of designing BHEs.

Groundwater flow has been proven to be potentially one of the most influential factors on BHEs; it was also determined to be an even more effective factor during times when the BHE is not operational, i.e. thermal recovery. Hence, the possibility of employing natural or artificial groundwater flow as a measure to improve the long-term thermal sustainability of closed loop geothermal heat pump systems needs to be further explored.

The effect of in-borehole factors, i.e. loop temperatures or grout thermal conductivity, on the heat exchange efficiency has been examined under semi-steady state conditions; however, in reality the state of heat transfer inside a BHE is highly transient. Thus, for a more accurate estimation of in-borehole properties on BHE performance it is suggested to further study them under transient state replicating the real-world conditions.

The practice of freezing the ground and benefiting from the latent heat of icing has been stated, as a theoretically effective underground energy storage method. Due to the limitation of the model used in this study, simulation codes capable of accounting for latent heat during icing-thawing of the groundwater, e.g. SUTRA-ICE, should be used. This can ideally be accompanied by laboratory experiments especially to test the practicality of this approach, e.g. damage from the ice expansion to heat exchanger pipes and the seal. Geotechnical concerns need also to be considered.

The dramatic effect of balance, or lack thereof, in system energy load, on the long-term performance and impact of multi-BHE systems has been observed almost at its extremes. It could be of interest to model some in-between cases in the future. It is also motivated to find the sensitivity of BTES systems to groundwater flow based on loop temperatures during storage and extraction phases, with non-storage ordinary multi-BHE systems with balanced energy load at one end.

Single borehole heat exchangers have been put in a number of heterogeneous environments with low complexity. As a future study proposal, multi-borehole systems could be placed in more complex settings. This could eventually demonstrate the amount of difference between an ideally laid out borehole array and a poor placement as well as the error emerged from not comprising the fracture hydraulic discontinuities.

This study sheds doubt on feasibility of thermal response testing for long-term planning of borehole heat exchangers in highly heterogeneous media like fractured rock. More research on interpreting TRT results in fractured rock is needed. This includes further computer simulation of hypothetical tests. Possibility of accurately estimating the apparent thermal conductivity of a borehole field through point measurements of thermal conductivity, and site investigation techniques is explorable.

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- **Dehkordi, S.E.**, R.A. Schincariol, and B. Olofsson. Effect of horizontal and vertical fractures on borehole heat exchangers. Intended for *The Bulletin of Engineering Geology and the Environment* (currently in manuscript format)

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