Thermal Performance and Sustainability of Borehole Heat Exchangers within Building Clusters

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Graduate Program in Geology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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Abstract

Geothermal energy has greatly increased in prevalence over the last 20 years. With many new installations, the desire to introduce geothermal energy into unused urban environments has increased. However, the urban environment has a great effect on the subsurface thermal profile, which may significantly influence geothermal systems. To test the effectiveness and efficiency of different geothermal systems in tight building clusters, as well as the effects of the system on the subsurface, a three-dimensional finite element model was developed. The model is based on an area of University of Western Ontario campus that has a geothermal system utilizing borehole heat exchangers. FEFLOW, a groundwater and heat flow modeling program was used to simulate the area and a geothermal system. It was found that geo-exchange systems on average retain 95% efficiency over time but did also reshape the subsurface thermal profile.

Keywords: Geothermal, building clusters, borehole heat exchanger, thermal transport, geo-exchange system, hydrogeology.
Acknowledgments

I would first like to thank Dr. Rob Schincariol for his unending patience, and support during this project. Rob, you took a chance on me when few others would have, and shared with me your knowledge and experience. You kept me focused and were always a calm and reassuring influence when the project seemed insurmountable. You understood my goals, and altered my project to match, preparing me for a future career, and for that I will always be grateful.

To my parents, thank you for your love and support. You believed in me and encouraged me to take a chance. We haven’t lived in the same place for years, but I always feel that you are with me. To my brothers, who never really knew what my work was, but were proud of me and encouraged my education just the same.

I would also like to thank my friends and colleagues, without many of you I would never have finished (without some of you I would have finished sooner, but the experience would have been lacking). To my office mate and friend Joelle Langford, I don’t think I could have managed without your help. From the early days of struggling with FEFLOW to the last, struggling with writing, you were always there with advice and a smile. To the RG’s, who made sure I kept my school-life balance and were always there to discuss and vent. And of course Nadine and Vienna, thank you for making the office so much brighter.
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Chapter 1

1 Introduction

Geothermal energy is a renewable form of energy derived from the heat of the earth (Banks, 2008). Geothermal energy can take many forms. Direct use systems, using low temperature geothermal, can be used for space heating of a single home, or on an industrial scale (Banks, 2008). High temperature geothermal, with temperatures greater than 180°C, can be used for electricity generation (Banks, 2008; Ellabban, et al., 2014).

Geothermal power has been steadily growing in prevalence, in the early 2000’s it was estimated at 10 Gigawatts (GW) globally, with 900,000 geothermal units installed (Barbier, 2002). This is an energy output of roughly 28,000 tetra joules (TJ), and could replace up to 15.4 million barrels of oil (Curtis et al., 2005). Given that Canada sold 1.9 million barrels of oil per day domestically in 2017, this may seem like a small amount (NRCAN, 2018). However, 98% of the 1.9 million barrels per day were for gasoline, diesel, and other purposes (NRCAN, 2018). Only about 38,000 barrels per day were used for heating, meaning that the geothermal energy production could replace Canada’s annual heating oil consumption. By 2012 total energy output had increased to 11.4 GW produced globally (Ellabban et al., 2014), and was at 12.6 GW by 2015 (Bertani, 2016).

A novel approach for existing buildings and building-clusters to save on heating costs and reduce carbon emissions is to utilize geothermal energy through ground source heat pumps (GSHP). The two most common systems are horizontal and vertical systems. Horizontal systems typically reach depths of up to 2m, are relatively cost effective to install, and provide acceptable thermal output (Banks, 2008). Unfortunately they require a large horizontal area to be effective, and in dense urban settings, this is not always feasible. Conversely, vertical systems require far less horizontal area, and operate at much greater depth, giving a more stable thermal regime (Banks, 2008). Vertical systems take the form of boreholes that are drilled anywhere from 30 m to 300 m depth.

Generally vertical geothermal systems are installed before or during construction of buildings and are ideally placed in a grid formation that discourages interference between individual
boreholes (Dehkordi and Schincariol, 2014). There are, however, many existing buildings that could benefit from the addition of geothermal systems by installation of said systems in the available urban spaces. These areas of existing infrastructure affect the subsurface thermal gradients (Ferguson and Woodbury, 2007). The impact of the urban heat island effect (UHIE) is well known, and is not limited to the alteration in urban climate. The UHIE extends its effects to the subsurface, influencing geothermal systems (Rivera et al., 2015). Studies have generally focused primarily on single boreholes with few buildings. This study used real-world functioning geothermal systems to create a computer model that will allow us to study the effectiveness of small borehole heat exchanger (BHE) fields, as well as the effects of urban environments on these systems and determine the viability of small borehole fields within tight building clusters.

1.1 Study Objectives

The purpose of this study is to create and develop a model to determine the effectiveness of BHE fields in a dense urban environment as well as the effects of geothermal systems on the subsurface thermal regime, based on a functional system. The specific area being modeled is the University of Western Ontario campus, with a focus on the buildings housing the Faculty of Engineering. In 2009 the Claudette MacKay-Lassonde Pavilion was built as an addition to the Faculty of Engineering, with a geothermal exchange system being added in 2011. Subsurface temperature recording instruments were installed at the same time as the geothermal system and began recording data when the system became active in September of the same year. The model will focus on the geothermal system and the surrounding area, which contains multiple buildings, and roadways, typical of an urban environment.

All models were created using FEFLOW (Finite Element subsurface FLOW and transport system), which is a finite element modelling program capable of simulating the subsurface groundwater flow and thermal transport of the study area in three dimensions. FEFLOW also contains a built-in tool for simulation of BHEs, which is the type of geothermal system used in this study. This allows for the simulation of the current two-BHE geothermal system, as well as simulation of a variety of larger BHE fields. Being a finite element modelling program allows for
the creation of flexible meshing, allowing for different densities within the mesh. This is important as it allows for the necessary mesh density at the geothermal system, while maintaining a computationally efficient mesh for the rest of the model.

This work will further advance the understanding of the effects of BHE systems in an urban environment already altered by anthropogenic thermal influences. While work has been done on this subject, this will be the first to incorporate data from an active BHE system in an urban environment which incorporates hydrogeological principles.

1.2 Thesis Organization

This thesis is presented in six chapters. The first introduces the study. The second chapter serves as a primer on geothermal energy systems as well as a literature review. The third chapter outlines the methods used to develop the FEFLOW models, the mathematical equations, the data collection, and the parameters used to create the models. The fourth chapter details the results of the model. The fifth chapter discusses the results, and the final chapter concludes the thesis, and provides direction for future work.
Chapter 2

2  Background Information and Literature Review

2.1  Geothermal Energy in Urban Environments

Geothermal energy is simply the utilization of the Earth’s natural heat at depth (Banks, 2008). The most common type of geothermal energy in urban areas is shallow geothermal, utilizing heat from just below surface to a maximum depth of 300 m (Younger, 2012; Rivera et al., 2016). Shallow geothermal systems can refer to either horizontal loops, or take the form of vertical heat pump systems, usually referred to as a borehole heat exchanger or BHE (Banks, 2008).

In urban environments, the thermal profile of the subsurface is altered by change in land use due to urbanization, this is known as the urban heat island effect (UHIE). The UHIE is driven by anthropogenic alteration of the environment, and has been well studied (Arnfield, 2003). As an area becomes more urbanized grass and tree cover is replaced by paved roads and buildings. The change from grass or other vegetation to asphalt or pavement allows for increased ground temperatures due to increased absorption of solar radiation, while the removal of trees reduces the amount of shaded area that would help reduce ground temperatures (Gorsevski and Luvall, 1998; Igun and Williams, 2018). Pavement and asphalt have been found to cause a 3°C increase in annual ground surface temperature, compared to grass, which can propagate up to 30 m into the subsurface (Taylor and Stefan, 2009). Figure 2-1 illustrates the increase in temperature due to urban environments.
Waste heat from buildings and other buried infrastructure such as sewers will also add to the increase in heat in the subsurface (Rivera et al., 2016). Sewer systems, can radiate heat into the subsurface at temperatures from 12°C to 25°C (Menberg et al., 2013), and heat flux from uninsulated basements, can cause heat bulbs to depths of 100 m or more over a few decades (Ferguson and Woodbury, 2004).

BHEs have been studied in urban environments with respect to their effects on the subsurface thermal regime (Rivera et al., 2015; Bayer et al., 2016); however less attention has been paid to the effects of urbanization on BHE functional efficiency. Previous work has explored the surface cover effects on BHE thermal plumes (Rivera et al., 2015), the potential for geothermal potential in urban environments (Rivera et al., 2016b), and the effects of building and groundcover on a single BHE system (Rivera et al., 2016). No work has yet to examine the effects of a multiple BHEs in an urban environment.
2.2 Borehole Heat Exchangers for Shallow Geothermal Extraction

Borehole heat exchangers for shallow geothermal extraction can be classified into two main types: open-loop and closed-loop. The open-loop BHE system is simply a borehole drilled to depth where groundwater is at the appropriate temperature for heating or cooling and a pump inserted to draw water (Banks, 2008). Open loop systems are those that actually remove water from the source (i.e. Lake, aquifer) and are “open” at the intake (Figure 2-2). They may be used for passive cooling and heating, or include a heat pump if they are to be used a significant source of heating (Banks, 2008). Open systems draw on groundwater and return used water to the supplied source, this means that open-loop systems have a high potential for environmental impact (Dehkordi and Schincariol, 2014b).

![Figure 2-2. An open-loop geothermal system showing the injection and production wells. Note that wells are open at the base (Self et al., 2013).](image)

In a closed-loop system the borehole groundwater is not removed, rather a set of sealed pipes are inserted in the borehole, which is grouted and sealed (Figure 2-3) (Banks, 2008). These pipes circulate a fluid, and rely on conduction from the surrounding rock for heating and cooling (Younger et al., 2012). The pipes are most commonly made from polyethylene and
polypropylene, due to their durability and flexibility. These pipes are either, single U-tube, double U-tube, or in a coaxial configuration (Figure 2-4) (Diersch et al., 2011). The U-tube varieties simply cycle through a “U” shaped pipe, while the coaxial is a “pipe within a pipe” and the inner pipe being the inlet and the outer pipe the outlet, or vice versa (Banks, 2008).

Figure 2-3. A closed-loop system, note this contains multiple loops in parallel (Self et al., 2013).

Figure 2-4. Schematics of (a) Single U, (b) Double U, and (c) coaxial heat exchangers as seen in cross section. Grey areas are the grout; white areas show the tube where fluid moves in (i) and out (o) (Dehkordi and Schincariol, 2014b).
The pipes themselves are filled with a fluid, usually a solution of ethanol or ethylene glycol that is cycled through the loop. At surface the heat exchanger loop will enter the building, and usually does so through the basement to avoid contact with the open environment. Some systems will also employ a heat pump connected to the heat exchanger to increase the efficiency (Floridies and Kalogirou, 2007). A heat pump is a device that increases the temperature difference to a circulation system, allowing the heat to be more efficiently used (Banks, 2008). The same principle can be applied to allow for cooling as well but in reverse.

BHE systems may be used for both heating and cooling, or simply store heating/cooling energy underground for later use. In these systems the energy extracted from the ground is roughly equal to the energy injected and are known as balanced systems (Banks, 2008). Systems that have a strong bias towards heating and cooling are considered unbalanced systems (Banks, 2008). A balanced system has the advantage of maintaining the thermal regime of the subsurface. Work by Dehkordi et al (2015) shows the effects of a balanced system compared to an unbalanced system. We can see in Figure 2-5 that after 25 years the balanced system has maintained equilibrium with the subsurface temperature, where the unbalanced heat extraction system has caused a large cooling anomaly to form.
Figure 2-5. Ground temperatures under balanced (A) and unbalanced (B) energy after 25 years. Note the same temperature and length scales. The cross symbols (×) show the location of BHEs Dehkordi et al., 2015).
2.3 Regional and Local Geology and Hydrogeology

The surface of much of southern Ontario is dominated by glacial sediments, with London, ON covered predominantly by glacial till (Chapman and Putnam, 1984; Schwartz, 1974). There are many distinct tills covering southern Ontario (Bajic and Dodge, 2011), however London is covered mainly by the Port Stanley till (Schwartz, 1974). The Port Stanley Till is mainly clayey silt, stone poor, and has a high plasticity (Bajic and Dodge, 2011). Till has a relatively low hydraulic conductivity, and often acts as a confining layer or aquitard (Schwartz and Zhang, 2003), which is the case for the Port Stanley till (Matrix Solutions Inc., 2014). Below the till lies the Catfish Creek Drift, a stony, silty to sandy till which is often over consolidated (Bajic and Dodge, 2011). Locally Catfish Creek Drift acts as an aquifer (Schwartz, 1974).

Below the glacial sediments lies the bedrock. There are many geologic units which appear regionally, but are not found within the local study area. For the purpose of this study, “local” refers to an area within or near by the model domain. Only geologic units which are present on the local scale, and thus impact this study, will be discussed.

Below the till lies the Dundee formation which is consistent through much of southwestern Ontario and is approximately 35 m to 45 m thick (Armstrong and Carter, 2010). It is medium to thick bedded fossiliferous limestones with minor dolostones (Armstrong and Carter, 2010). The limestone is generally considered impermeable and has little porosity; however it has fractured over large structural domes and is believed to be karstic in some locations (Armstrong and Carter, 2010; Schlumberger Water Services Inc., 2011). Where fractured, it may produce water, and can be considered a contact aquifer in many locals throughout southern Ontario (Armstrong and Carter, 2010).

The upper 2m of the Dundee are weathered and have a higher hydraulic conductivity. As a result it is considered a contact aquifer (Matrix Solutions Inc., 2014). All Devonian aged units have a
high hydraulic conductivity and are classified as aquifers (Waterloo Hydraulic Inc., 2007; Matrix Solutions Inc., 2014).

Beneath the Dundee is the Lucas Formation which combines the Anderson Member limestone and sandy limestone (Armstrong and Carter, 2010; Matrix Solutions Inc., 2014). The limestone is fine grained with medium bedding, and the sandy limestone is medium to coarse grained and massive to bedded, and very fossiliferous (Armstrong and Carter, 2010; Matrix Solutions Inc., 2014).

Below the Lucas formation is the Bois Blanc. This unit is a cherty limestone, fine to medium grained, with significant fossil inclusions (Armstrong and Carter, 2010). It ranges from 3 m to 50 m; this is consistent with the thickness seen in the drill records (Koepke, 1963; Armstrong and Carter, 2010). The formation has little or no visible porosity and contains little to no water (Armstrong and Carter, 2010). The Bois Blanc has a relatively low hydraulic conductivity when compared to the units above and below, classifying it as an aquitard (Matrix Solutions Inc., 2014).

The Bass Island formation is the last geologic unit in the model domain, and represents the upper Silurian-aged deposition. It is a crystalline dolostone with variable lamination and mud content (Armstrong and Carter, 2010). It may contain local breccias, and evaporite minerals, with rare fossil inclusions (Armstrong and Carter, 2010). The thickness ranges from 10 to 90 m regionally (Matrix Solutions Inc., 2014), which is consistent with drill records near the study site (see Appendix A). The Bass Island formation has little porosity and holds no water (Armstrong and Carter, 2010), but does have a relatively high hydraulic conductivity and is classified as an aquifer (Matrix Solutions Inc., 2014; Waterloo Hydrogeologic Inc., 2007).

A regional groundwater study of Middlesex and Elgin counties conducted by Dillon Consulting and Golder Associates Ltd. (2004) notes that there is a groundwater divide to the north of the study site, beyond which water flows in a north to north-western direction to Lake Huron. This means that water in the study area would flow south, to Lake Erie. Groundwater flow through both the overburden and bedrock is north to south, towards Lake Erie as well. A Tier Three
assessment by Matrix Solutions (2014) from neighboring Oxford County confirmed flow direction.

2.4 Study Site Geology, Hydrogeology, and Geothermal Regime

The study site is located on the grounds of the University of Western Ontario in London Ontario (17 T 477550 E 4761445 N). In the north of the city there is a large regional groundwater divide described in Chapter 2.3.3. Groundwater north of the divide flows towards Lake Huron, while water south of the divide flows towards Lake Erie (see Appendix: B). UWO campus sits south of the divide, and groundwater flows in a southerly direction.

The study site is a 450 m by 250 m area aligned with assumed groundwater flow, and is centered on the Faculty of Engineering buildings, and surrounding infrastructure (Figure 2-6A). The geothermal exchange systems are adjacent to the buildings, with the horizontal system is located on the eastern side of the court yard, and the vertical system to the west (Figure 2-6B).
Figure 2-6. A) Model domain and BHE location (red dot). B) Faculty of Engineering building with horizontal fields in blue, and BHE location (red dot).
The vertical system itself is made up of two active wells, and three monitoring boreholes (Figure 2-7). The monitoring boreholes contain a thermistor string with thermistors at 30 m, 45 m, 60 m, 75 m, and 90 m depth. One additional thermistor was attached to each of the outer-piping of the BHE at approximately 45 m depth (Figure 2-8).

Figure 2-7. Location of borehole heat exchangers (BHE) and monitoring boreholes (MB) in courtyard of the engineering buildings.
Study site geologic units were identified using drill core and drill logs from the boreholes used to install the heat exchangers as well as previous borehole studies done on University of Western Ontario’s campus (Judge, 1972; Digaletos, 2016). The BHE and monitoring boreholes were reviewed during drilling, but were not cored and only basic lithologies were identified. An examination of local and regional well logs was done to better identify lithology and continuity of overburden (see Appendix A). Regionally the overburden is largely dominated largely by till, with occasional glacial fluvial deposits. Local well records also show occasional fluvial deposits, but are mostly till-dominated.

Site-level groundwater flow direction is north-west to south-east, which is similar to regional flow direction (Figure 2-9). There is a topographic high to the north-west of the study area and topographic highs are often areas of groundwater divide ((Freeze and Cherry, 1979). As such, groundwater was assumed to flow the topographic high to low.
2.4.1 Geothermal Regime

A geothermal study on the University of Western Ontario (UWO) campus was completed by Judge and Beck (1969a), and further work on geothermal setting of both UWO and southern Ontario was done by Judge (1972). Temperature was found to be between 9°C and 9.75°C from 90 to 200 m depth. Temperature gradient for the same depth was found to be between 0.1 °C per 30 m and 0.2°C per 30 m.

The temperature inversion, the point at which temperature at depth changes from decreasing to increasing, was found to be at roughly 80 m (Judge and Beck, 1969b). As most of the underlying geologic units have similar thermal properties, the temperature increases with depth fairly uniformly (Figure 2-10).

Figure 2-9. Map of study area with waterways and elevation shown. Elevation is given by green lines, flow direction indicated by blue arrow and model domain outlined in red.
2.5 Climate

London, Ontario has an annual average temperature of 7.9°C, and a range between 12.7 °C and 3.0 °C (Environment Canada, 2018). Temperatures follow an asymptotic pattern, being highest in July and are lowest in January. Annual precipitation is 1011.5 mm per year, with 845.9 mm falling as rain mainly between April and November. Annual snowfall is 194.3 cm which occurs primarily between November and March. A summary of the climate data can be seen in Figure 2-11.
Figure 2-11. Climate normals 1981 to 2010 for London, ON (Environment Canada, 2018).
Chapter 3

3 Methods

3.1 Numerical Modeling

Simulation of the study site required software that could model both groundwater flow, and heat transport. The finite element modeling program FEFLOW was chosen as it is a 3D modeling program, has flexible meshing capabilities, and reliably simulates groundwater and heat flow. It is a reliable system and is widely used in both academic research as well as being an industry standard. This section will discuss the standard equations used by FEFLOW to simulate subsurface flow of groundwater and thermal transport.

3.1.1 FEFLOW

For modeling, there exist multiple methods, the finite difference, the finite volume, and the finite element methods (Anderson et al., 2015). Of the three, the finite element method is considered superior as its geometry is flexible, and can accurately apply boundary conditions in complex domains (Diersch, 2014). FEFLOW utilizes the finite element method and can solve the governing flow and heat transport equations in porous media (Diersch, 2014). In addition to groundwater and heat flow, FEFLOW also includes a BHE simulation as a boundary condition. The BHEs are represented as embedded 1D elements that are linked to nodes of the element mesh in a 3D model (DHI, 2016).

3.1.2 Groundwater Flow in Saturated and Unsaturated Models

FEFLOW is a mathematical model, and more specifically, a process-based model. To represent groundwater flow within a domain a process-based model utilizes principals of physics along with physical processes (Anderson et al., 2015). FEFLOW uses governing equations based on Darcy’s Law and conservation of mass to represent the process in the model domain, and boundary conditions to do the same at model boundaries (Anderson et al., 2015). Should the model be time-dependent, initial conditions are also required.
For fully saturated models the Darcy equation (Equation 3.1) is used as the governing equation to calculate groundwater flow. It is given as;

\[ q = -K_r(s)\mathbf{K}(\nabla h + \chi e) = -K_r(s)\mathbf{K}[(\psi + \chi)\mathbf{e}] \]  

(3.1)

where,

\[ q = \text{Darcy flux vector (m s}^{-1}) \]

\[ K_r(s) = \text{relative hydraulic conductivity (m/s)} \]

\[ \mathbf{K} = \text{tensor of hydraulic conductivity} \]

\[ h = \psi + z; \text{ hydraulic (or piezometric) head (m)} \]

\[ \chi = \text{buoyancy} \]

\[ e = \text{gravitational unit vector} \]

To accurately model the study site the vadose or unsaturated zone needed to be represented, as the unsaturated zone is an important thermal boundary. To represent flow in the unsaturated zone FEFLOW employs the Richards Equation (Equation 3.2) (DHI, 2016). The equation itself appears as;

\[ S_0 \cdot s(\psi) \frac{\partial \psi}{\partial t} + \varepsilon \frac{\partial s(\psi)}{\partial t} + \nabla \cdot q = Q \]  

(3.2)

Where,

\[ S_0 = \varepsilon \gamma + (1-\varepsilon)\Upsilon \text{ specific storage due to fluid medium compressibility (m}^{-1}) \]

\[ \gamma = \text{fluid compressibility} \]

\[ \Upsilon = \text{coefficient of skeleton compressibility} \]

\[ s(\psi) = \text{saturation} \]

\[ \psi = \text{pressure head (m)} \]
\( \varepsilon \) = porosity

\( q \) = Darcy flux vector \((m \ s^{-1})\)

\( Q \) = specific mass supply \((m \ s^{-1})\)

In Darcy’s Law hydraulic conductivity is constant, however with unsaturated soils the hydraulic conductivity becomes a function of saturation and matric potential. Additionally, in unsaturated media, the saturation levels will change with time, so the continuity principle is applied, forming the Richards equation (Hillel, 1998).

### 3.1.3 Thermal Transport

Heat flow in the subsurface occurs mainly through either conduction or advection (Anderson, 2005). Heat transport can be expressed by equation 3.3 (Domenico and Schwartz, 1998):

\[
\frac{\lambda'}{\rho'c'} \nabla^2 T - \frac{\rho_f c_f}{\rho'c'} \nabla (T \ q) = \frac{\partial T}{\partial t}
\]

(3.3)

Where

\( \lambda' \) = bulk thermal conductivity \((J \ m^{-1} \ s^{-1} \ K^{-1})\)

\( \rho' \) = bulk density \((kg \ m^{-3})\)

\( \rho_f \) = fluid density \((kg \ m^{-3})\)

\( \rho_s \) = solid density \((kg \ m^{-3})\)

\( c' \) = bulk specific heat capacity \((J \ kg^{-1} \ K^{-1})\)

\( c_f \) = specific heat capacity of fluid \((J \ kg^{-1} \ K^{-1})\)

\( c_s \) = specific heat capacity of solid \((J \ kg^{-1} \ K^{-1})\)
\( q = \) Darcy flux vector \((m \text{ s}^{-1})\)

And the bulk heat capacity and bulk thermal conductivities are represented as:

\[
\rho'c' = \varepsilon_f \rho_f c_f + \varepsilon_s \rho_s c_s \tag{3.4}
\]

\[
\lambda' = \varepsilon_f \lambda_f + \varepsilon_s \lambda_s \tag{3.5}
\]

Where

\( \varepsilon_f = \) Porosity (fluid phase)

\( \varepsilon_s = \) Porosity (solid phase)

In equation 3.3 the groundwater flux \((q)\), the product of the hydraulic conductivity \((K)\) and the hydraulic gradient \((i)\), is the defining factor for advective heat transport rate. The conductive portion of thermal transport equation is controlled by porosity in both the solid and fluid phase, as seen in equations 3.4 and 3.5.

### 3.1.4 BHE Thermal Transport

FEFLOW has a built in BHE simulation tool which was used in this study. BHEs are simulated in FEFLOW as embedded 1D elements linked to nodes along element edges in a 3D model (FEFLOW, 2015). FEFLOW provides two solution methods for BHEs, the Al-Khoury (2005) and a variation of the Eskilson and Claesson (1988). The Al-Khoury (2005) is a numerical solution and is best suited to short-term simulations (minutes to hours) (Diersch et al., 2011a). The Eskilson and Claesson (1988) is an analytical solution and is best suited to simulations over longer time periods (days to years) (Diersch et al., 2011a).

This study uses a BHE solution developed by Diersch et al. (2010, 2011a, 2011b), and is based on the Eskilson and Claesson (1988) solution. Diersch et al.’s work (2010, 2011a, 2011b) added to the original solution by generalizing the formula for BHE types, improving the point-to-grout method, improved thermal relationship of thermal resistance between BHEs, and direct non-
sequential coupling of 1D elements (Diersch et al., 2010). The BHE solution was tested and found to be efficient and precise, and reduced modeling times for multi-BHE systems (Diersch et al., 2010, Dehkordi and Schincariol, 2014).

3.2 Model Design and Application

3.2.1 Model Domain

When creating model boundaries, topography and groundwater flow direction were considered. Regional groundwater flow maps show that groundwater flow is north to south, in areas near London Ontario (Matrix Solutions, 2014). Topography was used to help refine flow direction, as points of high topography tend to be recharge zones, and low points are discharge zones (Freeze and Cherry, 1979). The study area is bounded on the NNW by Medway Creek, and the River Thames SSE as shown in Figure 2-8. A focused view of the model domain can be seen in Figure 3-1, showing the constant head boundaries. The boundary to the NNW was assigned a head value of 445 m, and the SSE boundary assigned 440 m. The boundaries running parallel to flow were considered no flow boundaries.
For the steady-state model the hydrogeological and thermal boundary conditions needed to be determined. The steady state model was required to simulate initial conditions prior to the transient model runs. Hydraulic head values were the first parameter to be set, with the inflow boundary at 245 m and the outflow boundary at 240 m. Head values were determined from potentiometric surface maps for overburden and bedrock aquifers from reports by Dillon Consulting and Golder Associates Ltd. (2004) and Matrix Solutions (2014). An average hydraulic gradient was estimated by taking several hydraulic gradient calculations using the afore mentioned potentiometric surface maps. The potentiometric surface map for each geologic unit was used to create an average value for the bedrock and the over burden which was later applied to the model. The average groundwater flow gradient between both reports was found to be 0.012, which is translates to a 5 m drop in head over the length of the model domain. This gradient was consistent for both the overburden, and ground rock layers. The height of the hydraulic head was approximated from regional equipotential maps (Dillon Consulting and Golder Associates Ltd., 2004), which is a regional map that includes the study area. Head is assumed to remain relatively constant throughout model run time of 20 years.
The model contains two thermal boundaries, one on surface and another at the base of the model. The boundary at model-base was derived from a geothermal study performed at UWO by Judge (1972). The study by Judge (1972) recorded temperature values at 183 m and 213 m depths. These temperature values were used to determine an estimate of the temperature at 200 m, the depth for the base of the model. The temperature at 200 m depth was calculated to be 9.6 °C. However, during model calibration a base temperature of 9.6 °C was found to be too high, and the temperature profiles would not be properly calibrated. Through sensitivity analysis a value of 9.4 °C was found to be a better fit. The 0.2 °C difference is small and may be caused by difference in equipment and measuring methods. Temperatures at depths of 200 m are relatively stable, and unaffected by climate shifts within the last 200 years (Pollak and Huan, 2000; Kukkonen et al., 2011). As such, the boundary was set as a Dirichlet type, or constant temperature boundary.

The surface boundary condition was derived from ground surface temperatures and not air temperature as they are quite different. Data from a study done in St. Paul, Minnesota that included ground surface temperatures (Taylor and Stefan, 2009) was used to provide ground surface temperatures. To ensure temperature values would be representative of London, climate normals from 1981-2010 for both cities were compared. Average annual temperature was found to be very similar, with a difference of 0.05°C. Solar radiation levels were also compared and both locations received similar levels. The only major difference was in precipitation, with St. Paul receiving about 15% less precipitation annually, and mostly in the winter months. It must be noted that ground cover has a dramatic effect on the ground surface temperature. Data from an Environment Canada research station located at UWO’s research farm was not used as it only had data for grass and bare soil. The annual average temperature was found to be 10.1°C for grass and 13.2°C for asphalt/concrete. The surface boundary was also set as a Dirichlet type boundary, a constant 10.1°C and 13.2°C set for grass or asphalt/concrete respectively.

Buildings and sewer systems were not included in the steady-state model, and were added to a transient model as part of the spin-up process (see chapter 3.2.3). In the transient model both were set as Dirichlet type boundary conditions, with basements set at 20°C, and sewers at 18.5°C.
3.2.2 Model Properties

With no hydrogeological reports in the study area, hydraulic conductivity had to be estimated from reports and studies from Middlesex and Oxford County. A report from by Dillon Consulting and Golder Associates Ltd. was available and was used to determine the overburden values, as the report itself focused on shallow flow (Dillon Consulting and Golder Associates Ltd., 2004).

The overburden and bedrock layers in the study area extend regionally and have been included in neighboring counties for regional studies. Hydraulic conductivity values were estimated based on a report by from Matrix Solutions (2014) in neighboring Oxford County. All values were compared to hydraulic conductivity ranges for rock and sediment type. Minimum and maximum values for hydraulic conductivity were taken from Matrix Solutions (2014) report, and a suitable intermediary value was used in initial model simulations. To ensure geologic layers were consistent, the BHE and monitoring boreholes were compared to borehole logs for nearby boreholes. The first is a borehole located near the BGS building on UWO campus drilled in 1963 for a geothermal study (see Appendix: A), and the second was for a nearby building, the Sisters of St. Joseph, which had a BHE system installed in 2005 (see Appendix: A). The drill logs from these boreholes were compared to the current UWO borehole logs, which were found to be consistent.

During model calibration, several sensitivity analyses were run to determine the effects of certain variables on the model. It was found through these analyses that models using the minimum hydraulic conductivity values produced results much more similar to measured data than the intermediary or the maximum values (see Appendix E). As such, the minimum value was used in all future iterations of the model. Vertical hydraulic conductivities were set as one order of magnitude lower than horizontal, as is common practice (Schwartz and Zhang, 2003). Hydraulic conductivity values can be seen in Table 3-1.
Table 3-1. Model properties.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Hydraulic Conductivity [m s(^{-1})]</th>
<th>Effective Porosity</th>
<th>Thermal Conductivity [W m(^{-1}) K(^{-1})]</th>
<th>Heat Capacity [MJ m(^{3}) K(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K_{x,y})</td>
<td>(K_z)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glacial Till</td>
<td>1x10(^{-7})</td>
<td>1x10(^{-8})</td>
<td>0.3</td>
<td>3.72</td>
</tr>
<tr>
<td>Weathered contact</td>
<td>1x10(^{-4})</td>
<td>1x10(^{-5})</td>
<td>0.15</td>
<td>3.05</td>
</tr>
<tr>
<td>Dundee</td>
<td>1x10(^{-5})</td>
<td>1x10(^{-6})</td>
<td>0.05</td>
<td>3.05</td>
</tr>
<tr>
<td>Lucas Formation</td>
<td>1x10(^{-5})</td>
<td>1x10(^{-6})</td>
<td></td>
<td>3.05</td>
</tr>
<tr>
<td>Bois Blanc</td>
<td>1x10(^{-5})</td>
<td>1x10(^{-6})</td>
<td></td>
<td>3.56</td>
</tr>
<tr>
<td>Bass Island</td>
<td>1x10(^{-5})</td>
<td>1x10(^{-6})</td>
<td></td>
<td>4.18</td>
</tr>
</tbody>
</table>

Thermal conductivity measurements were taken from (Judge, 1972), approximately 1km from the borehole drill site. Judge (1972) did not include overburden; these values were estimated from Banks (2008) based on sediment type. Volumetric heat capacity values were not available in any regional or local study, and have been estimated based on lithology from literature values (Banks, 2008). Porosity was also measured by Judge (1972), however effective porosity was required. Effective porosity was estimated from measured porosity values from Schwartz and Zhang (2003). For all thermal property values, see Table 3-1.

3.2.3 Model Input and Spin-up Process

To ensure the model had been properly calibrated, model spin-up results were made to match the recorded thermistor data from the UWO boreholes for a 2 month period prior to the activation of the geothermal system. Thermistor data from 30 m, 45 m, 60 m, 75 m, and 90 m depth was used to create a thermal profile that would be matched by the model. This data can be seen later in Chapter 4.
Initial modeling attempts using present day infrastructure resulted in a system that had greater heat accumulation in the upper 80 m than monitoring borehole data. It was determined that the steady state model was creating the heat accumulation and that the spin-up needed to be completed in phases. There were three main phases of the FEFLOW modelling process; the initial steady state spin-up, a multi-step transient spin-up, and the final working model which would serve as initial conditions for future models. The steady state model would create initial conditions for transient models. The transient model spin-up would start in 1942, when the study area had little in the way of infrastructure (Figure 3-2). Buildings and roads would be added to the transient model as they appeared in the air photo record until August 2011.

![Figure 3-2. Air photo of UWO campus as it appeared in 1942. The model domain has been approximately outlined in red.](image)

As discussed before, the initial steady state model brought the system to a thermal and hydrogeological steady state prior to any major infrastructure being added to the model. Initial models used the annual average temperature value for grass cover (10.1°C), however this still resulted in a higher subsurface temperature than recorded. As the steady state model was devised to start the model in 1942, changes in climate had to be taken into account. Using climate records
it was determined that the average annual air temperature had increased by roughly 1°C since 1942 compared to the present. As such the steady state model and part of the transient spin-up uses 9.1°C as the surface temperature boundary condition.

The transient spin-up contains 12 models or “steps”, and brings the model domain from 1942 to August 30th, 2011. The spin-up adds buildings and roadways as they appear in the air photo record, with each new “step” being a continuation of the prior model. The model steps and the accompanying additions to the model can be seen in Table 3-2.

**Table 3-2. List of transient model spin-up steps by year with features added or removed.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1942</td>
<td>Western road and Lambton drive, Cronyn Observatory, small building north-east of Western road and Lambton drive. Average annual temperature used as surface temperature boundary condition.</td>
</tr>
<tr>
<td>1955</td>
<td>Cronyn Observatory parking lot.</td>
</tr>
<tr>
<td>1960</td>
<td>Spencer Engineering building (original structure).</td>
</tr>
<tr>
<td>1965</td>
<td>Law Building (original structure). Parking lot in northwest near Helmuth Hall.</td>
</tr>
<tr>
<td>1967</td>
<td>Lambton drive becomes two lanes, Alumni Hall.</td>
</tr>
<tr>
<td>1971</td>
<td>Spencer Engineering building addition, addition in center of engineering building. Law building addition (complete). Expanded roads, current sewer system (approximate).</td>
</tr>
<tr>
<td>1978</td>
<td>Small building (surrounded by parking lot NE of Western/Lambton) removed, greenspace remains.</td>
</tr>
<tr>
<td>1989</td>
<td>Thompson Engineering and Boundary Layer Wind Tunnel buildings.</td>
</tr>
<tr>
<td>1998</td>
<td>Huron Hall added, grass temperature 10.1°C and asphalt 13.2°C.</td>
</tr>
<tr>
<td>2003</td>
<td>Green space surrounded by Springett parking lot gone. Spencer addition (beside Cronyn). Change to monthly average temperature surface temperature boundary condition (time series added).</td>
</tr>
</tbody>
</table>
Architectural plans for the Engineering, Wind Tunnel, and Thompson Engineering buildings were reviewed and were found to have an average basement depth of 2.5 m (see Appendix D). Buildings without detailed elevation data were assumed to have the same basement depth. Building basements were represented by a 20°C temperature boundary condition (Ferguson and Woodbury, 2004; Menberg et al., 2013). The heat from the basement walls are not represented as it has been demonstrated through modeling and experimentation that heat loss from the walls is mainly through the atmosphere (Menberg, 2014). The buildings themselves are considered impermeable to water and as such the elements defining the interior were deactivated so there would be no flow through them.

Asphalt, concrete and grass cover temperatures were represented by their respective annual average values with the exception of the final 10 years of spin up when the average monthly temperatures were used. During the final 10 years of spin up the ground surface temperatures were represented by the monthly average temperature values. These average monthly values replaced the previous temperature boundary condition at surface. This was done to provide more accurate results for the final stages of the spin up. It should be noted that the average annual temperature was reduced by 1°C until 1998 to account for climatic shift.

Sewer systems were added based on known locations from building design documents (Hyde, 2018). Menberg et al. (2013), suggests temperature for sewage between 12°C and 25°C, so an average of 18.5°C was used. This was compared with temperature values for incoming sewage from nearby sewage treatment facility and determined to fall within an acceptable range (City of London, 2018).

Following the spin-up, the model was calibrated by comparing simulated subsurface temperatures to field data from the UWO monitoring boreholes (see Chapter 4.2). Care had to be taken to add each feature as it appeared. Prior attempts at spin-up tried to simplify the process by starting the model later in UWO’s history, however this required buildings to be included in the steady-state model, and this was found to have poor model calibration.
3.2.4 Model Discretization

When generating a mesh for modeling, care must be taken when determining the most effective number of elements. While a large number of elements will give accurate results, too many elements will be computationally taxing. The main focus of the study is to review the effectiveness of the BHE system given the thermal interference of anthropogenic sources. The mesh was constructed in 2D (with later conversion to 3D) using the triangle meshing tool in FEFLOW as it is ideal for complex meshes that include lines and points. Prior to meshing buildings shapes and locations were exported from maps created using the geographic information system ArcGIS. The buildings were added as shape files as this would allow for easier and more consistent mesh elements when discretizing. The same process was repeated for the BHEs and monitoring boreholes. During mesh creation, building walls, BHEs, and monitoring borehole locations were discretized to a finer degree. The buildings received finer discretization because the walls of the basement areas were originally planned to be modeled. However it was later determined that the heat loss through basement walls was mostly connected to the atmosphere (Thomson and Rees, 1998; Emery et al., 2007). When the wall-refinement was found to be unnecessary; the total number of elements in the model was reviewed and found to contain 524,832 elements, FEFLOW can accommodate up to 3 million elements, so this was deemed acceptable. The buildings, and thus the building wall refinements were built as part of the framework for FEFLOW’s mesh generation, meaning that any change to the building wall refinement would require a rebuild of the model from the initial pre-meshed stage. The model did not have lengthy run times it was decided that the building wall refinement would remain as they did not add excessive load to computation.

Diersch et al. (2010) suggest calculation of the optimal nodal spacing to provide optimal accuracy. The equation for optimal nodal spacing is given as;

\[ \Delta = \exp(\alpha) r_{virtual} \]  

(3.7)

and
\[ \alpha = \frac{2\pi}{n \tan\left(\frac{\pi}{n}\right)} \]  

(3.8)

where;

\( n = \) number of surrounding nodes (6 in this case),

\( r_{\text{virtual}} = \) virtual radius of BHE

When calculated it was found that the optimal spacing was 0.46 m and care was taken during meshing to create the correct distance between nodes.

In addition to the fining of features, the option to force Delaunay triangulation, also known as the Delaunay criterion, was selected. This option maximizes the minimum angle of the triangular elements so that small sliver-shaped triangles are avoided. Or, put another way, prevents triangles with two very small acute angles and a single very large obtuse angle. This allows for more accurate and consistent solutions.

Once the 2D mesh was complete and Delaunay criterion tested for consistency, the model was converted to 3D. This was done by adding elevation data for the slice, and then copying the top slice to a depth of 200 m. The vertical discretization scheme can be seen in Table 3-3, and is based on distance between the slices. As the anthropogenic factors such as artificial surface cover and roadways were deemed to have an important impact, thermal transport from surface was determined to be of great importance. For this reason the vertical discretization is higher at the surface and coarsens at depth. This allows for accurate modeling of the thermal influence of the surface.

**Table 3-3. Vertical discretization scheme**

<table>
<thead>
<tr>
<th>Slice</th>
<th>Thickness (m)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-11</td>
<td>0.1</td>
<td>0 - 1.0</td>
</tr>
<tr>
<td>12-22</td>
<td>0.25</td>
<td>1.0 - 3.5</td>
</tr>
<tr>
<td>23-27</td>
<td>0.5</td>
<td>3.5 - 6</td>
</tr>
<tr>
<td>28-31</td>
<td>1</td>
<td>6 - 10</td>
</tr>
<tr>
<td>32-72</td>
<td>5</td>
<td>10 - 200</td>
</tr>
</tbody>
</table>
The lower layers have a relatively low discretization as it was determined through sensitivity analysis that thermal transport was not influenced by further discretization below 10 m depth.

The original 2 BHE model contains 524,832 elements, and 271,008 nodes. To test various BHE field configurations, additional fining of the mesh was required so allow for optimal BHE nodal spacing. Models with additional BHEs will have a higher mesh density in the BHE fields and a higher mesh and node count.

3.3 Model BHE Specifications

The vertical geothermal system used by the CMLP building is comprised of two single u-tube BHEs extending to 90 m depth. The pipe dimensions and operational requirements were provided by engineers controlling heating, ventilation, and air conditioning (HVAC) and from their monitoring system. The specifications for the pipe dimensions can be seen in Table 3-4.

Table 3-4. BHE model specifications

<table>
<thead>
<tr>
<th>Name</th>
<th>BHE</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole diameter</td>
<td>0.15</td>
<td>m</td>
</tr>
<tr>
<td>Distance between pipes</td>
<td>0.075</td>
<td>m</td>
</tr>
<tr>
<td>Inlet pipe diameter</td>
<td>0.0381</td>
<td>m</td>
</tr>
<tr>
<td>Inlet pipe wall thickness</td>
<td>0.0035</td>
<td>m</td>
</tr>
<tr>
<td>Outlet pipe diameter</td>
<td>0.0381</td>
<td>m</td>
</tr>
<tr>
<td>Outlet pipe wall thickness</td>
<td>0.0035</td>
<td>m</td>
</tr>
<tr>
<td>Inlet pipe thermal conductivity</td>
<td>0.45</td>
<td>J m(^{-1}) s(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Outlet pipe thermal conductivity</td>
<td>0.45</td>
<td>J m(^{-1}) s(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Grout volume thermal conductivity</td>
<td>2.00</td>
<td>J m(^{-1}) s(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Refrigerant volumetric heat capacity</td>
<td>4.05</td>
<td>(10^6) J m(^3) K(^{-1})</td>
</tr>
<tr>
<td>Refrigerant thermal conductivity</td>
<td>0.42</td>
<td>J m(^{-1}) s(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>Refrigerant dynamic viscosity</td>
<td>2.75</td>
<td>(10^{-3}) kg m(^{-1}) s(^{-1})</td>
</tr>
<tr>
<td>Refrigerant density</td>
<td>1.045</td>
<td>(10^{3}) kg m(^3)</td>
</tr>
</tbody>
</table>
The BHE editing tool in FEFFLOW allows users to select different computational methods for BHE modeling. This study uses the Eskilson and Claesson (1988) method, as it is ideal for long-term modeling. The addition of the 2-BHE system saw a drastic increase in the time required to run the model. A change in the numerical parameters of the model was required. The number of iterations per time step was reduced to 1, and the error tolerance was reduced to $10^{-4}$.

### 3.3.1 Operational Cycle

The BHE system shares heating and cooling duties with a horizontal geothermal system. Under a normal operational cycle, every Tuesday after 06:30, the system switches between the horizontal loop and the vertical loop. However, if the return water temperature is greater than 18°C or lower than 10°C the BHE system starts (Larkin, 2018). The geothermal system is controlled and monitored by a data management tool known as enteliWEB. Records from enteliWEB were used to confirm the 7-days-on, 7-days-off schedule. There were periods of inactivity for both horizontal and vertical systems; however the 7-days-on, 7-days-off schedule remained consistent for the available records. The model used the 7 day pumping cycle, but also tested a continuous operational cycle. The UWO BHE system operates in conjunction with a horizontal geothermal system, and the 7-day cycle is the result of the two systems sharing the heating and cooling load. Most BHE systems do not operate on an intermittent cycle, and simply operate continuously. To test the effects of continuous operation, models were run that swapped the 7-day cycle for a continuous operational cycle.

### 3.3.2 Pumping-Rate and Inlet Temperature

A review of the BHE monitoring data showed that inlet temperature was dependent on pumping rate. The inlet temperature is recorded, regardless of the operational cycle. When the vertical BHE is in an “off cycle” the exchanger fluid either does not circulate, or is pumped at a very low rate. This essentially results in the fluid equilibrating to the temperature of the maintenance room where the system is housed. Thus inlet temperature readings can only be used when they coincide with an active pumping cycle. As stated before, the active cycle averaged 7-days-on, 7-days-off, but this schedule varied at times. A complete set of both inlet temperature and pumping
rate was available from April 2017 to September 2018. However, prior to this date data was unavailable for pumping rate, meaning inlet temperature could not be determined.

The pumping rate, when active, was found to vary between 10 m$^3$ day$^{-1}$ and 60 m$^3$ day$^{-1}$, however these extreme values appeared at time when the BHE system was beginning or ending its activation cycle. During operation the average was calculated to be 40 m$^3$ day$^{-1}$ with variation within about 4 m$^3$ day$^{-1}$.

For modeling purposes, the 40 m$^3$ day$^{-1}$ value was assigned as the pumping rate. Inlet temperature values and pumping rates were compared for the same time period, and temperatures corresponding to pumping rates below 10 m$^3$ day$^{-1}$ were discarded. This was done because the BHE system will often record pumping rates below 10 m$^3$ day$^{-1}$ in the hours after the BHE system is changed to an “off cycle”.

An average inlet temperature was calculated for each month (Table 3-5), and was used to simulate inlet temperatures in the model.

**Table 3-5. Average monthly inlet temperatures.**

<table>
<thead>
<tr>
<th>Month</th>
<th>Inlet Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3.40</td>
</tr>
<tr>
<td>February</td>
<td>4.33</td>
</tr>
<tr>
<td>March</td>
<td>3.81</td>
</tr>
<tr>
<td>April</td>
<td>16.41</td>
</tr>
<tr>
<td>May</td>
<td>26.58</td>
</tr>
<tr>
<td>June</td>
<td>34.46</td>
</tr>
<tr>
<td>July</td>
<td>34.99</td>
</tr>
<tr>
<td>August</td>
<td>35.84</td>
</tr>
<tr>
<td>September</td>
<td>34.88</td>
</tr>
<tr>
<td>October</td>
<td>32.51</td>
</tr>
<tr>
<td>November</td>
<td>12.66</td>
</tr>
<tr>
<td>December</td>
<td>3.80</td>
</tr>
</tbody>
</table>
A balanced system, as discussed in Chapter 2.4.3, has an approximately equal heating and cooling load. These inlet temperatures show a slight bias towards cooling. We see six cooling months (May to October), and two transitionary months (April and November) where the system may alternate between heating and cooling (Larkin, 2018). The remaining four months (December to March) are the heating months, as indicated by their low inlet temperatures.

FEFLOW has the option for the use of time series, allowing variables to change during model simulation. To model the system as accurately as possible, two time series were created to run concurrently and repeat every 365 days during simulation. The first was the inlet temperature, where the temperature changes for each month. The second is the pumping rate, which switches between 40 m$^3$ day$^{-1}$ and 0.01 m$^3$ day$^{-1}$, every seven days.

### 3.4 BHE Simulation Calibration and Testing

Once the model was calibrated by matching recorded and simulated subsurface temperatures, the BHEs were added. The active BHE system would be used to both calibrate the system, and test long-term effects of the UWO geothermal system. The BHE system was also calibrated using subsurface temperatures. Simulated and recorded temperatures for a 30 day period beginning at the time of BHE activation were compared. The results are shown later in Chapter 4.2.2. After calibration the active BHE model was run for 20 years to test the long-term effects of UWO’s BHE system. During this time the numerical parameters and computational methods discussed in chapter 3.3 were determined through sensitivity analysis to provide the best functioning model (see Appendix E).

After the active BHE model was successfully calibrated, the model parameters were altered to test three scenarios for each BHE field spacing. The first scenario would simply be a continuation of the active BHE system, but scaled-up to a BHE field and the second scenario would see the addition of an upgradient BHE field. The third scenario would be similar to the first, but operate on a continuous cycle. A later addition to the model would test a 10 m spaced
field with BHEs 150 m in length. Before larger BHE fields could be added the location of the fields needed to be set, and the area defined. As it contained the active BHE system, the courtyard of the CMLP building was used as the location for the BHE fields. The BHE field area includes the courtyard and ends roughly at sidewalk, and attempts to minimize overlap with the horizontal system. This field has an area of 1700 m² and can be seen in Figure 3-6. A secondary upgradient field was planned to be included in the study and was outlined at this time as well. For simplicity of modeling, the upgradient field was given the same area (1700 m²), and was constructed as a simple rectangle close to the Law building (Figure 3-3).

Figure 3-3. BHE fields in relation to buildings. The buildings and roads are light blue, and grey respectively. The CMLP filed is hatched brown, and the Law building field is green.

Properly spaced boreholes are necessary to ensure efficient use of space while minimizing interference between BHEs. Signorelli et al (2005) noted that BHE spacing was important to
reduce thermal interference of a BHE field, and suggested a minimum of 7 m to 8 m. Dehkordi et al (2015) studied distance between boreholes and suggested spacings between 5 m and 10 m between each borehole. The performance of BHEs with set spacings was found to vary with changes in groundwater flow and BHE load (Dehkordi et al., 2015). As such, the spacings suggested by Signorelli et al (2005) and Dehkordi et al (2015) were tested in this study. The BHE spacings tested were 5 m, 7.5 m, and 10 m.

The active BHE model was modified by refining the mesh in the defined BHE field area. The field area was recreated in ArcGIS and a grid points spaced 5 m apart was overlaid. This grid was imported into FEFLOW to ensure distance between BHEs was consistent (Figure 3-4). The mesh was adjusted where necessary so nodes were centered on a grid point. This was done because the nodes were used for BHE simulation. Surrounding nodes were adjusted to allow for ideal nodal spacing (see Chapter 3.1.4). This process was repeated for a 7.5 m and 10 m filed spacing. These models would run with the 7-day operational cycle used for the active BHE model, as well as the same BHE specifications, and inlet temperature. The 5 m, 7.5 m, and 10 m models would later be revisited to test a continuous operational cycle. These models are identical in meshing and BHE parameters to the 7-day operation cycle models described above, but would operate continuously.
To construct the upgradient BHE field, a defined area and grid overlay was made in the same manner as the CMLP BHE field. The mesh in the defined area beside the Law Building was refined and nodes adjusted as was done for the CMLP Field. The upgradient field was given the same BHE spacing to match its downgradient counterpart. All fields would operate with the same BHE specifications, inlet temperatures, and the 7-day operational cycle.

The final model was created to test a field with BHEs extending to 150 m. Due to increased computational requirements of the 150 m BHE length which resulted in high run-time, only one extended BHE model was created. The model was based off of the 10 m spaced field model, and simply required the BHEs be extended from 90 m to 150 m. This model would use the same BHE specifications, inlet temperatures, and the 7-day operational cycle.

Each scenario was tested with the three BHE field spacings, with the later addition of the extended BHE field. For simplicity, each model was named for its spacing distance, and its
scenario. Table 3-6 lists the model, the location of its field(s), operational cycle, and number of BHEs.

Table 3-6. Borehole field locations and the corresponding spacing and operational cycle.

<table>
<thead>
<tr>
<th>Model</th>
<th>BHE Field Location(s)</th>
<th>Operational Cycle</th>
<th>Number of BHEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m A</td>
<td>CLMP Courtyard</td>
<td>7 days-on 7 days-off</td>
<td>69</td>
</tr>
<tr>
<td>5 m B</td>
<td>CLMP Courtyard and Law building</td>
<td>7 days-on 7 days-off</td>
<td>69</td>
</tr>
<tr>
<td>5 m C</td>
<td>CLMP Courtyard</td>
<td>Continuous</td>
<td>69</td>
</tr>
<tr>
<td>7.5 m A</td>
<td>CLMP Courtyard</td>
<td>7 days-on 7 days-off</td>
<td>36</td>
</tr>
<tr>
<td>7.5 m B</td>
<td>CLMP Courtyard and Law building</td>
<td>7 days-on 7 days-off</td>
<td>36</td>
</tr>
<tr>
<td>7.5 m C</td>
<td>CLMP Courtyard</td>
<td>Continuous</td>
<td>36</td>
</tr>
<tr>
<td>10 m A</td>
<td>CLMP Courtyard</td>
<td>7 days-on 7 days-off</td>
<td>18</td>
</tr>
<tr>
<td>10 m B</td>
<td>CLMP Courtyard and Law building</td>
<td>7 days-on 7 days-off</td>
<td>18</td>
</tr>
<tr>
<td>10 m C</td>
<td>CLMP Courtyard</td>
<td>Continuous</td>
<td>18</td>
</tr>
</tbody>
</table>
Chapter 4

4 Results

This chapter is divided into three sections. The first set of results presented is recorded field and system data. These include both the temperature data from the monitoring wells, and the data from the CMLP building’s HVAC monitoring system. The recorded results were used to create realistic parameters for the modeled geothermal systems, and used to calibrate the model. The second section discusses the results of the model calibration. Finally, the third section discusses the results of the various model simulations.

4.1 Recorded Field and BHE Operational Data

4.1.1 Thermistor Data

Figure 4-1 shows the temperatures recorded by the thermistors at various depths for the three monitoring boreholes. We see that the temperature of the subsurface decreases from 30 m to 90 m. We also see that temperatures are steady until August 12th, when there is a slight rise in temperature; this corresponds to a test of the BHE system. On September 1st, the BHE system is activated. The period prior to activation was used to calibrate the model to ‘background’ thermal conditions prior to BHE activation.
Figure 4-1. UWO Field temperature over time. Values prior to September 1st, 2011 represent ground temperatures prior to the activation of the BHE system. Monitoring boreholes 1, 2, and 3 are represented by a solid line, dashed line, and a dotted line respectively. The depth of the thermistor data is indicated on the chart.

Figure 4-2 shows data from monitoring borehole 3, with monitoring boreholes 1 and 2 showing similar results. From this figure we see the change in temperature over time after activation of the BHE system. We can see the temperature oscillations throughout the year as the system changes from cooling to heating. Periods of increased ground temperature correspond to the BHE system actively cooling, as system injects energy into the subsurface. Decreased ground temperature corresponds to periods of heating as energy is extracted by the BHE. The first year of operation has the most consistent data and was used to calibrate the simulated BHE for the
model. After the first year of data some thermistors began to fail leading to an uncharacteristic drop.

**Figure 4-2.** Recorded field temperature over time after BHE activation for monitoring borehole 3.
4.1.2      Geothermal System Data

4.1.2.1      BHE System Data

EnteliWEB records BHE fluid temperature as it enters the BHE loop as well as the pumping rate of the cycled fluid. This data was used to create the inlet temperatures and pumping rate (see Chapter 3.3.2) for the BHE simulations. Table 4-1 shows the data from an active day of the BHE system. We can see that the pumping rate is relatively consistent, but there is some variation. We can also see that the inlet temperature does change throughout the day, reacting to the building heating and cooling requirements. One may also notice the system records pumping rate and temperature every 30 minutes, but there are some significant gaps where recording errors have occurred, with over 2 hours missing between the 15:11 and 17:42 timestamp. The cause of the errors is unknown (Larkin, 2018)

Table 4-1. Sample of inlet temperature and pumping rate data used to create average pumping rate and inlet temperature.

<table>
<thead>
<tr>
<th>Time</th>
<th>Pumping rate (m³ day⁻¹)</th>
<th>Inlet temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/04/2017 6:41</td>
<td>43.48</td>
<td>10.31</td>
</tr>
<tr>
<td>03/04/2017 7:11</td>
<td>43.96</td>
<td>9.70</td>
</tr>
<tr>
<td>03/04/2017 7:41</td>
<td>43.47</td>
<td>9.50</td>
</tr>
<tr>
<td>03/04/2017 8:11</td>
<td>43.96</td>
<td>9.30</td>
</tr>
<tr>
<td>03/04/2017 8:41</td>
<td>44.13</td>
<td>9.10</td>
</tr>
<tr>
<td>03/04/2017 9:11</td>
<td>43.55</td>
<td>8.90</td>
</tr>
<tr>
<td>03/04/2017 9:41</td>
<td>44.26</td>
<td>8.90</td>
</tr>
<tr>
<td>03/04/2017 10:11</td>
<td>43.80</td>
<td>8.90</td>
</tr>
<tr>
<td>03/04/2017 10:42</td>
<td>43.16</td>
<td>8.70</td>
</tr>
<tr>
<td>03/04/2017 11:11</td>
<td>43.39</td>
<td>10.91</td>
</tr>
<tr>
<td>03/04/2017 12:42</td>
<td>42.17</td>
<td>19.77</td>
</tr>
<tr>
<td>03/04/2017 15:11</td>
<td>43.62</td>
<td>19.77</td>
</tr>
<tr>
<td>03/04/2017 17:42</td>
<td>42.46</td>
<td>20.15</td>
</tr>
<tr>
<td>03/04/2017 18:12</td>
<td>43.21</td>
<td>19.96</td>
</tr>
<tr>
<td>03/04/2017 21:42</td>
<td>43.74</td>
<td>11.69</td>
</tr>
<tr>
<td>03/04/2017 22:12</td>
<td>43.79</td>
<td>19.01</td>
</tr>
<tr>
<td>03/04/2017 22:42</td>
<td>42.59</td>
<td>20.34</td>
</tr>
<tr>
<td>03/04/2017 23:12</td>
<td>42.77</td>
<td>19.96</td>
</tr>
</tbody>
</table>
4.1.2.2 Energy Data

Energy total for one year of operation was calculated from temperature change between inlet and outlet temperature values. Table 4-2 shows the energy total for each month, as well as the annual total energy. We can see that system produces the most energy in the summer months, making the system cooling-dominated. November has a much lower value as the system was not used for much of the month.

Table 4-2. 1 Year Energy Total for Active BHE System.

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>2,666</td>
</tr>
<tr>
<td>Feb</td>
<td>3,740</td>
</tr>
<tr>
<td>Mar</td>
<td>4,290</td>
</tr>
<tr>
<td>Apr</td>
<td>5,667</td>
</tr>
<tr>
<td>May</td>
<td>8,847</td>
</tr>
<tr>
<td>Jun</td>
<td>13,769</td>
</tr>
<tr>
<td>Jul</td>
<td>11,504</td>
</tr>
<tr>
<td>Aug</td>
<td>16,570</td>
</tr>
<tr>
<td>Sep</td>
<td>7,126</td>
</tr>
<tr>
<td>Oct</td>
<td>7,645</td>
</tr>
<tr>
<td>Nov</td>
<td>706</td>
</tr>
<tr>
<td>Dec</td>
<td>5,009</td>
</tr>
<tr>
<td>Total</td>
<td>87,541</td>
</tr>
</tbody>
</table>

The CMLP building’s energy requirements for heating and cooling are supplied mainly by a steam and cool-water system. They are supplemented by the geothermal system that includes the both vertical and horizontal systems and a supplemental hot-water system. Table 4-3 summarizes the energy used by the geothermal system for heating and cooling, and the main
steam heating system. Energy for the main cooling system was not available; however given the increase in energy output by the BHE system during the cooling months, it is possible cooling requirements would match, or exceed the annual heating requirements. 

The energy for the geothermal system is given as a whole and is not subdivided into the vertical or horizontal systems. Using the calculated annual energy output of the BHE system (Table 4-2) we see that it accounts for approximately 20% when compared to the total annual energy of the geothermal system.

<table>
<thead>
<tr>
<th>Table 4-3. Energy requirements for heating and cooling of CMLP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual steam heat energy Total (MJ)</td>
</tr>
<tr>
<td>Annual geothermal energy total (MJ)</td>
</tr>
<tr>
<td>Total Annual Energy</td>
</tr>
</tbody>
</table>

4.2 Model Calibration

The calibration process for the model was completed in two parts. The first was the calibration of the modeled subsurface prior to the activation of the geothermal system. The second calibration was the for the BHE system.

4.2.1 Pre-Geothermal System Calibration

To ensure the spin-up process had simulated the thermal profile of subsurface, it was necessary to compare the post spin-up thermal profile to the recorded data from the monitoring wells, prior to the activation of the geothermal system. The monitoring wells were installed approximately two months prior to the activation of the geothermal system on UWO campus. The thermal profile of the subsurface is shown in Figure 4-3. Here we see temperature at depth for each of the three monitoring boreholes. We can see that there is noticeable temperature variation between the boreholes, most notably at 60 m depth. The temperature values appear to diverge with depth, but consolidate once again at 90 m. While this may be due to some geologic feature such as fractures in the bedrock causing increased groundwater flow resulting in small temperature
differences, it is unlikely as no drilling logs show a fracture zone. It is most likely that the thermistors have shifted position, likely during installation, and are not at their proper depth.

Figure 4-3. Temperature vs depth profile of the UWO monitoring boreholes.

Modeled subsurface temperatures prior to the addition of BHEs were compared to the recorded thermistor data for calibration. The modeled data is from the final spin-up step (see Chapter 3.2.3), which had observation points to record temperature at the same location and depths as the thermistors in the monitoring boreholes. Figure 4-4 shows the comparison of the two data sets. The modeled data appears as a single thick line. This is because the modeled data has almost no variation, and the slight differences are likely due to variation in the model solutions. We see that the modeled temperature matches the field data best at 30 m and 90 m, also where the recorded data is most consistent. The modeled temperatures deviate from field data with depth, but differences are never greater than 0.3°C. Field temperatures are consistently warmer than modeled temperature data, which supports the idea that some geologic features such as fractures
in the bedrock are subtly altering the temperatures at these depths. However, the field data for monitoring borehole 3 is most consistent with the field data, and is very closely aligned to the modeled data. So it may be that the thermistors in monitoring boreholes 1 and 2 are not set at their assigned depths, and the temperature difference between field data for borehole 3. Given the small variation and potential causes for the temperature differences, the model was considered calibrated.

![Temperature vs Depth](image)

**Figure 4-4.** Temperature vs depth profile of the UWO monitoring wells compared to simulated temperatures. The prefix “F” denotes field data, and the prefix “M” denotes modeled data.

### 4.2.2 Calibration of BHE

After calibration of the model, the geo-exchange systems were added to the model. The vertical system was added using FEFLOW’s BHE software, and the specifications were estimated using the EnteliWEB system.
The geo-exchange system on UWO campus was activated August 30th, 2011. At this time the system was not run on the 7-day operational cycle. The BHE system was instead operated for 12 hours a day, for five days, with one day of inactivity. This 6-day cycle was repeated for several weeks, and was likely used as a test for the geothermal system and monitoring equipment. The first four weeks saw a consistent schedule for activity and this time period was chosen to calibrate the BHE model.

The inlet temperature was estimated from the thermistors attached to the active wells, at 45 m depth and determined to be approximately 20°C. The average pumping rate of 40 m³ day⁻¹ was not used during this initial time period, as test showed increased subsurface temperatures due to higher pumping rate. During sensitivity analysis a pumping rate of 20 m³ day⁻¹ was found to be optimal, as higher pumping rates resulted in increased subsurface temperature.

The comparison of modeled and recorded data for monitoring borehole 1 can be seen in Figure 4-5. The simulated data has a larger range of temperatures, especially at greater depth, however the trends are similar and temperatures vary by less than 1°C in most cases. Figure 4-6 shows a one-to-one plot demonstrating the similarity in temperature trends. We can see that the modeled data is close to the recorded field data at 30 m and 90 m, but has some variation between 45 m and 75 m. In both the subsurface thermal profile, and BHE calibration and the modeled temperatures were warmer for the middle thermistors. The temperature variation is likely due to the lithology. All thermistors sit in the limestone bedrock, with the exception of the 30 m thermistor which sits in the glacial till, 2 m above the bedrock contact. The cause of the temperature difference between 45 m and 75 m may be due to localized fractures in the limestone that facilitates the movement of warmer water through the area between 45 m and 75 m. Simulations showed that increased hydraulic conductivity increased the temperature for these depths. The BHE calibration starts off with the 30 m and 90 m thermistors close to the 1:1 line, but deviate over time (Figure 4-6). This is due to the estimates made for the inlet temperature and flow rate. The operational parameters of the BHE system were being tested and no record of the pumping rate or inlet temperature from this early period was available.
Figure 4-5. Comparison of simulated and recorded data over time. Data with the "M" prefix denotes Modeled data, while "F" denotes field data recorded by thermistors.
Figure 4-6. One-to-one plot of field and measured temperatures at depth over time. Each point indicates temperature for a day from August 30th, 2011 (left) to September 30th, 2011 (right). The black line represents the 1:1 line.

4.3 Simulation Results

The following results are those of the simulated BHE fields. These results test the spacings and scenarios outlined in Chapter 3.4. The results are organized into two main sections. The first is Energy Exchange, which will detail the energy output and efficiency of the simulated BHE systems. The second is the Subsurface Effects, which details the changes in subsurface thermal profile due to the various BHE spacings and scenarios.
4.3.1 Energy Exchange

The energy a system is able to produce over the 20 year lifespan of the system is given by the total energy exchanged. Energy for BHE systems is injected for cooling and extracted for heating. In balanced systems the energy difference between injection and extraction is close to 0, and the large the difference the more a system is unbalanced. This study defines the total energy exchanged as the absolute value of the sum of injected and extracted energy. Table 4-4 shows the total energy exchanged as well as the average annual energy exchanged. The active BHE system exchanged the least amount of energy over the 20 year run, and the 5 m spaced field exchanged the most. We see that the fields with the least distance between BHEs, and thus the most BHEs per area, exchanged the most energy. The difference in energy exchanged is proportional to the decrease in number of BHEs. For example, the 7.5 m spaced field contain about half the number of BHEs as the 5 m spaced field, and exchange roughly half the energy.

Table 4-4. Total annual average energy exchanged.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>Active BHE (MJ)</th>
<th>5 m A (MJ)</th>
<th>7.5 m A (MJ)</th>
<th>10 m A (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-year Energy Total</td>
<td>3,299,864</td>
<td>105,944,489</td>
<td>57,166,388</td>
<td>28,776,633</td>
</tr>
<tr>
<td>Annual Average</td>
<td>164,993</td>
<td>5,297,224</td>
<td>2,858,319</td>
<td>1,438,832</td>
</tr>
</tbody>
</table>

The energy exchanged remains largely unchanged with the addition of an upgradient BHE field (Figure 3-6) as shown in Table 4-5. When the 7-day operational cycle is substituted for a continuous pumping cycle for scenario C, we see a nearly double increase in energy exchanged. The 7-day pumping cycle for scenario A results in 183 days of BHE activity, and the continuous pumping cycle operates for 365 days. Scenario C increases the annual days of operation by 100% compared to scenario A, but exchanges only 75% more energy. This suggests that the increase in energy from continuous operation does come at the cost of decreased energy exchange efficiency. The extended BHE system is similar to scenario A, except that the BHEs are extended in length from 90 m to 150 m. This increased the BHE length by 67%, but did not see the same increase in energy. The extended BHE field saw an increase of 52% in energy exchanged over scenario A. Both the extended BHE field and the continuous operational cycles
offer additional energy at the cost of system efficiency. Due to drilling costs the continuous system would appear to be the superior choice, but long-term costs of continuous operation would need to be considered.

Table 4-5. Comparison of model scenarios.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>10 m A</th>
<th>10 m B</th>
<th>10 m C</th>
<th>10 m Extended BHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Total (MJ)</td>
<td>28,776,633</td>
<td>28,671,096</td>
<td>50,459,151</td>
<td>43,923,598</td>
</tr>
<tr>
<td>Annual Average (MJ)</td>
<td>1,438,832</td>
<td>1,433,555</td>
<td>2,522,958</td>
<td>2,196,180</td>
</tr>
</tbody>
</table>

To test the effects of infrastructure on the system, as well as other factors such as the unsaturated zone and groundwater flow, five additional models were run. These models have the same number of elements and nodal spacing as well as the same BHE spacing and operational parameters as the 10 m spaced, 7-on-7-off model (10 m A). The only exceptions are models where the BHE length was halved to 45 m to test the effects of infrastructure on a BHE system that would be influenced by nearer surface temperatures. Table 4-6 displays the results of these simulations.

Table 4-6. Comparison of infrastructure, unsaturated zone, and groundwater flow effects on energy exchange.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>10 m A</th>
<th>No Infrastructure</th>
<th>No Infrastructure or unsaturated zone</th>
<th>No Infrastructure, unsaturated zone, or groundwater flow</th>
<th>BHE length 45 m</th>
<th>BHE length 45 m no infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Total (MJ)</td>
<td>28,776,633</td>
<td>29,421,478</td>
<td>29,665,325</td>
<td>24,232,460</td>
<td>14,350,427</td>
<td>14,742,205</td>
</tr>
<tr>
<td>Annual Average (MJ)</td>
<td>1,438,832</td>
<td>1,471,074</td>
<td>1,483,266</td>
<td>1,211,623</td>
<td>717,521</td>
<td>737,110</td>
</tr>
</tbody>
</table>
Table 4-6 shows that there is no appreciable difference between the 10 m A model and the models where infrastructure has been removed and the case where the unsaturated zone is not explicitly modeled (a slight increase of 2% and 3% respectively). The lack of groundwater flow as well as no infrastructure and unsaturated zone does have a more significant impact on the energy exchanged, decreasing the energy exchanged by 16%.

With the BHE length reduced by half to 45 m, we see that the energy exchanged is also reduced by half. This is understandable as 50% of the BHE length has been removed. When the infrastructure is not included in the spin-up and the BHEs are kept at 45 m length we see a 49% decrease in average annual energy exchange. Much like the full-length BHE simulations, it seems that the infrastructure has little effect on the energy exchanged, even when the BHE length is shorter with more influence from surface.

The BHE systems are nearly balanced and this is due to the CMLP, like most large buildings, being cooling dominated. In a balanced system the energy injected and the energy extracted equal zero, or close to zero. This depends on the scale of energy being exchanged of course. Figure 4-7 compares an average year of the 5 m A energy exchange rate to an idealized perfectly balanced system. The nearly balanced system is moderately asymmetrical and has more energy values with a positive exchange rate, indicating energy injection. For an average year the 5 m A system injects 3.1 million MJ and extracts 2.4 million MJ, leading to a 0.7 million MJ injection imbalance. This is seen in all spacings and scenarios.
Figure 4-7. Comparison of a nearly balanced system and a balanced system. The nearly balanced system is the average annual energy exchange rate of the 5 m A field.

4.3.2 Energy Exchange Ratio

To compare the efficiency of the model spacings and scenarios, the energy exchange ratio was devised. This is a dimensionless ratio that compares the energy exchanged in each year to the energy exchanged in the first year, and is given by (Equation 4.1);

\[
\frac{\text{Energy exchanged for given year}}{\text{Energy exchanged for year 1}}
\]  

(4.1)

The first year of every BHE system exchanges the largest amount of energy as the subsurface allows for greater heat dispersion before being altered by the BHE system. By comparing the
annual energy exchanged for subsequent years, we are able to see the decline of energy exchanged and thus, efficiency, over time. Figure 4-8 shows the three spacings for scenario A, as well as the active BHE system. We can see a sharp decline in annual energy exchanged in the first five years and gradually flattening out of the BHE field models, but not in the active BHE system. The flattening of the curve reflects a system reaching energy exchange equilibrium with the subsurface as thermal gradients are altered. The active BHE system, being only two BHEs, reaches this equilibrium within the first 2 years, and decline of energy exchanged from that time is just over 1%.

While there is some variation, all BHE field spacings appear to lower in energy exchanged proportionally, and after 20 years all spacings are within 0.1% of one another. The 5 m A system sees the most dramatic drop within the first 4 years of operation, but further decline in energy exchanged is within 1% for the remaining years. This is followed closely by the 7.5 m A system which has reached annual energy exchange stability after 5 years, and the 10 m A, after 7 years. The data shows that systems with smaller BHE spacing, and therefore a larger number of BHEs in a given area, will reach equilibrium with the subsurface faster. The active BHE system supports this as well, as the two BHEs are spaced approximately 5 m apart. When comparing the overall efficiency, we see that the 10 m A scenario maintains the most efficient energy exchange ratio for the model time period, and the 5 m A has the least. However, this difference is very small and after 10 years the difference between 10 m A and 5 m A energy exchange ratios is 0.1%, and remains so until the end of the model run. The BHE fields stabilize at about 95%, meaning they are retaining 95% of their original operational efficiency.
Figure 4-8. Comparison of modeled active BHE system and BHE fields energy exchange ratios over 20 year period.

When comparing the model scenarios for the 10 m spacing, there is a noticeable difference in energy exchange ratios. We see the addition of an upgradient BHE system (10 m B) has reduced the energy exchange efficiency after 20 years (Figure 4-9). The influence of the upgradient system begins at the 5 year mark, and reduces the system efficiency over time. However, after 20 years of operation there is only a 0.9% reduction in annual energy exchanged. This may be a result of the 10 m spacing to store more energy in the subsurface of the field, and thus mitigate the effects of the upgradient system.

The continuous operational system, 10 m C has a shape to the curve. The small “jumps” as seen in the energy exchange ratio are likely model instabilities from the system solver (Figure 4-8). The numerical parameters, such as error tolerance of the model and the number of iterations,
were not adjusted between models. This was done to allow for direct comparison between the models, but has in some cases negatively impacted the model solution. The “jumps” likely represent FEFLOW’s governing equations oscillating between solutions that are close, but not quite correct. No model errors or issues occurred during scenario C models, and the plotting of the energy exchange ratio was the only indication of errors in the model data. While this makes the data questionable, it does not mean it is entirely incorrect. The sections of the graph with oscillating data should be ignored, but the remaining data can be studied. We can see that continuous operation has reduced the efficiency of the system over time, even more so than the introduction of an upgradient field. The 10 m A system’s intermittent 7-day schedule would allow some thermal recovery during the inactive weeks, whereas the continuous operation of the 10 m C system would not have any such period of recovery. However the reduction of 1% efficiency over 20 years is hardly significant considering the increase in energy exchanged for a continuous operational cycle.

The extended system has the greatest reduction in energy exchanged over time. Its BHEs extend 150 m, and should presumably take advantage of the decreased temperature gradients at depth. The system uses the same operational parameters as the 10 m A system, and is nearly identical, save for the additional 60 m of length. The difference in the energy exchange ratio may be due to poor optimization of the extended system.
4.3.3 Energy per BHE

Energy per BHE was calculated by dividing the energy exchanged by the number of BHEs in a given field. Table 4-7 shows the results for energy per BHE over the total 20 year simulation, and the average energy exchanged per BHE per year. While the active BHE system exchanged the least total energy, it had the highest energy per BHE. We can see that the energy per BHE increases as BHE spacing increases. This shows that increasing the number of BHEs in a fixed area will have a negative impact on efficiency of the BHE field. This is due to the thermal interference between boreholes. The resulting increase in energy may be worthwhile given the overall reduction in efficiency. The 5 m A scenario is 4% less efficient annually than the 10 m A scenario, but has a total energy exchange almost four times larger (see table 4-3). Given the

Figure 4-9. Comparison of modeled energy exchange ratios for different scenarios over 20 year period.
increase in total energy, a small reduction in efficiency for tighter spaced BHE fields is negligible.

**Table 4-7. Total and average annual energy exchange per BHE for different spacings.**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Active BHE</th>
<th>5 m A</th>
<th>7.5 m A</th>
<th>10 m A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per BHE over 20 years (MJ)</td>
<td>1,649,932</td>
<td>1,535,427</td>
<td>1,587,955</td>
<td>1,598,702</td>
</tr>
<tr>
<td>Average annual energy per BHE (MJ)</td>
<td>82,497</td>
<td>76,771</td>
<td>79,398</td>
<td>79,935</td>
</tr>
</tbody>
</table>

The introduction of the upgradient field (scenario B) also seems to have very little effect on the energy per BHE. This may be due to the upgradient field being sufficient distance away from the downgradient field so that its influence is not seen until the later years (see Chapter 4.4.2). The thermal plume of the upgradient field is likely to cause some thermal interference. The most notable changes come from the continuous operational cycle and BHE systems of extended length (Table 4-8). For the continuous operational cycle we see that doubling the active days per year for the BHE system increases the energy per BHE compared to the 7-day cycle scenario. As with total energy exchanged, doubling the active days for the BHE system does not equate to a doubling of energy per BHE. Extending the length of BHEs in a field will also result in increased energy per BHE. For systems operating in a limited area and tight BHE spacing, extending BHE length would be an ideal way to increase energy exchanged per BHE.

**Table 4-8. Total and average annual energy exchange per BHE for different scenarios.**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>10 m B</th>
<th>10 m C</th>
<th>10 m A Ext BHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per BHE over 20 years (MJ)</td>
<td>1,592,839</td>
<td>2,803,286</td>
<td>2,440,200</td>
</tr>
<tr>
<td>Average annual energy per BHE (MJ)</td>
<td>79,642</td>
<td>140,164</td>
<td>122,010</td>
</tr>
</tbody>
</table>

It is worth noting that while an increase in BHE length increases the energy exchange per BHE, extending the length does decrease the energy exchanged per meter length. Table 4-9 compares BHE per meter length, for a single BHE. The energy per meter length for scenarios A, B, and C reflect the energy per BHE, however the extended system is noticeably lower. The extended
BHE system was modeled with the same inlet temperatures and pumping rate as the 90 m BHE systems. During model calibration, it was noted that adjusting the pumping rate did affect the thermal profile of the subsurface when inlet temperature was constant (see Chapter 4.2.1). The actual active BHE system’s pumping rate was calibrated to equilibrate with the subsurface over a 90 m length. For the extended length, using the same inlet temperature and pumping rate would mean that the BHE fluid is mostly equilibrated with the subsurface by 90 m depth, and any further fluid flow due to length is really not adding much. Adjustments to the pumping rate and possibly the inlet temperature as well may increase the energy exchanged per meter.

Table 4-9. Energy exchanged per meter length.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>10 m A</th>
<th>10 m B</th>
<th>10 m C</th>
<th>10 m A Ext BHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per meter (MJ)</td>
<td>17,763</td>
<td>17,698</td>
<td>31,148</td>
<td>16,268</td>
</tr>
</tbody>
</table>

We can see that the extended BHE system has the lowest energy exchanged, so there may be an optimal length for a BHE system. This would depend on many factors such as subsurface thermal gradient, as well as drilling and operational costs.

4.4 Subsurface Temperature Change

The simulated effects of the different BHE spacings and scenarios on the subsurface thermal profile are presented in this section. To view the effects, a cross-section of the area around the CMLP was used and follows the direction of groundwater flow. Figure 4-10 shows the location of the cross-section in relation to the model domain.
Figure 4-10. Cross-section location (green line) in relation to BHE fields. Buildings are yellow and the blue arrow indicates groundwater flow.

Prior to the simulation of any geothermal systems, a cross-section view was taken to serve as a reference. Figure 4-11 shows the subsurface after the spin-up (chapter 3.2.3) was complete and before simulation of BHE systems. This and all other cross-sections are oriented along the path of groundwater flow, with flow moving from left to right of the figures. We can see the effects of infrastructure present in the subsurface thermal regime. The grey section on the upper left of Figure 4-12 represents a section of the CMLP building. To the left of the building we see a small section of grass cover, which can be easily identified by the lower temperatures at surface and steeper thermal gradient below (see Figure 4-12). The effects of the building on the subsurface show a stark contrast to the grass-cover. We see the thermal plume created by the building, both vertically and laterally. One should note the change in depth of the 12°C isotherm from grass-cover area to the area underneath the building and extending along the direction of groundwater
flow. This isotherm has been lowered by almost 30 m, from its highest point below the grass-cover. Also of note is the large high-temperature area to the right of the building. This area represents the asphalt and concrete cover of roadways/parking lots and sidewalks. We can see the heat-bulb of the building, roughly outlined by the 14°C isotherm sharply retreating to surface approximately 60 m form the building’s edge. From there the 12°C isotherm does not rebound as the 14°C isotherm did once removed from the building’s influence. The thermal influence of the asphalt and concrete has kept the temperature gradient much lower than areas beneath grass-cover.

Figure 4-11. Cross-section after spin-up and prior to geothermal system activation.
Figure 4-12. Focused view of grassy area next to CMLP building section.

For comparison a model was spun-up using the same methods as described in chapter 3.2.3 that did not include any infrastructure, whose cross-section is seen in Figure 4-13. A difference plot was constructed that compares the difference in temperature between the pre-BHE with infrastructure (seen in Figure 4-11) to the no-infrastructure spin-up, and can be seen in Figure 4-14. We can see there is a large temperature variation is highest near surface, and decreases with depth. At 50 m depth there is a 2°C temperature difference, and at approximately 80 m depth the two models have no temperature variation.
Figure 4-13. Cross section of CMPL area prior to BHE activation, with no infrastructure added.

Figure 4-14. Difference plot comparing the temperature difference between the infrastructure and no infrastructure models prior to BHE activation.
4.4.1 Active BHE System

The active BHE system after a year of operation is shown in Figure 4-15. The effects appear quite dramatic, with the thermal influence of the two BHEs thrusting downwards, however the surrounding thermal gradients show otherwise. However, the 12°C and 10°C isotherms have not shifted much except for a small area of influence within a few meters of the BHEs. The 14°C and 12 °C isotherms near the BHEs are nearly parallel; however within 5 m to 10 m they return to their original position that is perpendicular to the BHE orientation. This is also seen in the 10°C isotherm, but to a lesser degree due to its depth. This shows that the BHEs have not had much impact within the first year.

Figure 4-15. Subsurface thermal profile of active BHE system after 1 year of operation.

After 5 years of operation we begin to see a thermal plume developing beyond the immediate area of the BHEs (Figure 4-16). The 14°C isotherm has not expanded its overall lateral distance,
but has moved downward by about 5 m. We also see this in the 12°C and 10°C isotherms. The shape of the 12°C (and to some degree the 14°C) isotherms that was parallel in the first year of operation has begun to “lean” towards the right of the image, which is the direction of groundwater flow. It is worth noting that isotherms upgradient of the BHEs remain largely unchanged, save for the immediate areas that are being heated through conduction. Any changes on the upgradient side of the BHE are likely to be caused by the thermal influence of roads and buildings, rather than the BHE. We can also see that there are two small divots in the 10°C isotherm that appear to be “lifted” just below the base of the BHEs. These appear to be remnants of the cooling-plume that is created during heat extraction. This indicates that the thermal signal produced by the injection and extraction cycles remains throughout the year. This shows that equilibrium has not yet been reached.

![Subsurface thermal profile of active BHE system after 5 years of operation.](image)

**Figure 4-16.** Subsurface thermal profile of active BHE system after 5 years of operation.

After 20 years of operation we see the thermal plume of the BHE system has continued its expansion (Figure 4-17). The 14°C isotherm has seen lateral and downward movement; however this is mostly below depths of 10 m. This is likely due to the seasonal thermal influence of the surface which generally fades by 10 m depth (Taylor and Stephan, 2008). Additionally, the
water-table for this section of the model is 8 m – 10 m depth, so any thermal transport would rely on conduction only, as well as competing with seasonal temperature signals. The 10°C and 12 °C isotherms have also been lowered and flattened over time as the plume expands. The 10 °C isotherm now rests at 135 m elevation, 25 m below its original placement prior to BHE activation and 20 m since the first year of operation.

Upgradient we see there has been little change in the thermal profile. Isotherms beneath the building remain consistent with their location 15 years prior, with only the 12°C and 10 °C seeing downward movement. It may be that thermal equilibrium was reached early below the building and the constant thermal flux from the basement has maintained balance to a certain degree. We can see that there is thermal influence of infrastructure however. In the upper right corner of Figure 4-15 and Figure 4-16 we see the 12°C isotherm forming an “S” shape. The area upgradient of the cross-section is overlain by a roadway, as well as a building further up. In Figure 4-17 we see a section of this “S” shape has been replaced by a warmer thermal signal, caused by increased expansion of an upgradient plume. The 10°C isotherm divots below the BHEs identified in Figure 4-16 have been essentially erased. We can see a nearly imperceptible divot below the right BHE that is all that remains to identify the prior heat extraction signal. It would appear that the BHE system has reached, or is close to a thermal equilibrium with the subsurface.
Figure 4-17. Subsurface thermal profile of active BHE system after 20 years of operation.

For comparison, a model was run that omitted the active BHE system. Figure 4-18 shows the same cross-section after 20 years but without the influence of the BHEs. Firstly we see that the upgradient thermal profile is identical between the two models, and only begins to deviate about 10 m from the BHEs. The 14°C isotherm has expanded laterally under the influence of the BHEs, but only by a 1m – 2m. When looking at the position of the isotherms at the model boundary we see the vertical expansion of the BHE plume has moved the 12°C and 10°C isotherms about 6 m compared to the no-BHE model. This results in a roughly 1% change in thermal gradient. For ease of comparison, difference plots for the active BHE can be seen in Appendix: E.
4.4.2 Effects of BHE Field Size on Subsurface Thermal Transport

After the effects of the active BHE system on the subsurface thermal regime were investigated, testing of BHE fields was completed. This section compares the results of subsurface thermal transport between the 5 m A and 10 m A scenarios, as they represent the largest and smallest BHE fields respectively.

After a year of operation the influence of the BHE field can start to be seen. The 10 m A field has an BHE field temperature ranging from 12°C to 18°C, averaging 15 °C. The 10°C isotherm below the field has been moved to a depth of 100 m (Figure 4-19). The 10 m field’s internal isolines have a pronounced peak-and-valley shape, due to the distance between the BHEs which inhibits thermal interference. There are small upward inflections in the 10°C isoline below two boreholes that are cut by the cross-section, which are due to a period of energy extraction that caused the upward shift in the isotherm. This is similar to the 10°C “zones” seen in the active

Figure 4-18. Subsurface thermal profile, with no BHE system, after 20 years of operation.
BHE system (see Figure 4-16). The 5 m A field has many more BHEs and its thermal influence is well defined (Figure 4-20). While it does exhibit a peak-and-valley shape near the bottom of the BHE field, it is muted compared to the 10 m A field. The BHE field temperature has higher temperatures ranging from 16°C to 20°C, averaging about 19°C. The 5 m field is about 5°C warmer than the 10 m A field. The 10°C isotherm beneath the 5 m A field is at a depth of 105 m.

Figure 4-19. Subsurface thermal profile of 10 m spaced BHE field after 1 year of operation.
After 5 years the 10 m A BHE field temperature has become much more homogenous (Figure 4-21), and the dramatic peak-and-valley shape seen in Figure 4-18 is not as prevalent. This can also be seen in the BHE field temperatures range, from 14 to 18°C, with an average of 16.8°C. The 5 m field by comparison was already fairly uniform in BHE field temperature, but has become even more so (Figure 4-21). The 5 m field an internal field temperature between 18°C and 22°C, averaging about 21°C. The temperature difference has decreased to roughly 4°C between the two fields. This is likely due to the fact that the bedrock and sediments of the 5 m A field have equilibrated faster due to the larger number of BHEs compared to the 10 m A field. The denser BHE field has less area to store injected heat and has begun to reach an equilibrium temperature much soon than the 10 m A field. This means the 5 m A field will likely not increase its internal field temperature much more, but will expand its thermal plume further. The expansion of the 5 m A plume does exceed that of the 10 m A field. The 10°C isotherm below the 5 m field is now at 120 m depth, and the same isotherm below the 10 m A field is at 115 m depth. It should be noted that the 10°C isotherm at the model boundary is at 95 m depth for both
models. This is the same for the active BHE system for the same time period (Figure 4-18). This shows that the thermal plume from either field has not yet reached the model boundary.

Figure 4-21. Subsurface thermal profile of 10 m spaced BHE field after 5 years of operation.
Figure 4-22. Subsurface thermal profile of 5 m spaced BHE field after 5 years of operation.

After 20 years the 10 m A BHE field temperature has increased, and the thermal influence of individual BHEs can be seen outlined by the 18°C isotherms (Figure 4-23). This can also be seen in the 5 m field where BHEs are highlighted by the 22°C isotherms (Figure 4-24). 10 m A field temperatures have not greatly increased and range, from 16 to 20°C, with an average of 17.6°C. The 5 m field has similarly remained temperature between 18°C and 22°C, averaging about 21.5°C.

The expansion of the 5 m A plume has moved the 10°C isotherm to 140 m depth, and the same isotherm below the 10 m A field is now at 130 m depth. The horizontal expansion has been accentuated with time, and can be easily observed in both models. We see the 10 m A field’s 14°C isotherm forming a “>” shape that has just made contact with the model boundary. The 5 m A 14°C isoline takes the same shape, but we can see it has moved much farther beyond the model boundary.

For ease of comparison, difference plots for 5 m and 10 m spacing can be seen in Appendix: E.
Figure 4-23. Subsurface thermal profile of 10 m spaced BHE field after 20 years of operation.
4.4.3 Effect of Upgradient BHE Field

The addition of an upgradient BHE field had little effect on the BHE energy exchange, but there were changes to the thermal profile. We see changes in the subsurface thermal profile upgradient within the first year (Figure 4-25). The continuous 12°C isotherm seen near surface and close to the upgradient edge of the single field model (Figure 4-19) has been broken due to the encroaching effects of the upgradient field. The thermal plume upgradient is small and has not interfered with the downgradient field.
Figure 4-25. Subsurface thermal profile of 10 m spaced BHE field with upgradient field effects after 1 year of operation. The red arrow indicates the location of the broken 12°C isotherm.

The slow movement of the upgradient plume resulted in little change in the upgradient thermal profile and had not yet reached the downgradient system. At the 10 year mark we do begin to see changes in the downgradient CMLP field. Figure 4-26 shows the 10 m B field after 10 years of operation, while Figure 4-27 shows the 10 m A field after 10 years for comparison. The most notable change is the increased size of the 18°C isotherms within the BHE field. In the 10 m B field the three 18°C isotherms closest to the upgradient field are wider and longer, indicating increase heat build-up. An average of the internal temperatures showed the 10 m A field to be 17.3°C and the 10 m B field to be 17.6°C, a relatively minor temperature difference.

It should be noted that the thermal plume downgradient of the 10 m B field is the same as that of the 10 m A field. However, there is no movement of the isotherms below the BHE field between the two 10 m A and B fields, indicating that the thermal influence of the upgradient system has not affected the thermal profile below the BHE extent.
Figure 4-26. Subsurface thermal profile of 10 m spaced BHE field with upgradient field effects after 10 years of operation.
Figure 4-27. Subsurface thermal profile of single 10 m spaced BHE field after 10 years of operation.

After 20 years of operation we see significant expansion of the 18°C isotherm within the BHE field, as well as development of a 20°C isotherm (Figure 4-28). We can also see that the lateral expansion has increased, as is evident by the downgradient 14°C isotherm extending farther into the model border. We also see that the 10°C and 12°C isotherms are 5 m lower below the 10 m B field. Internal field temperature average for the 10 m B field was found to be 18.3°C, compared to 17.6°C for the 10 m A field.
Figure 4-28. Subsurface thermal profile of 10 m spaced BHE field with upgradient field effects after 20 years of operation.

The 10 m B field is 0.7°C warmer than the 10 m A field, which has resulted in lower energy exchange and energy per BHE. However, the reduction in energy efficiency is less than 0.5%. An additional 10 years were simulated for the 10 m B system to better understand the effects of the upgradient system. Figure 4-29 shows the CMLP field after 30 years of operation with an upgradient field. We see that there is very little change after 30 years, and that the 18°C isotherm from the upgradient field entering from the left of the figure has not traveled more than a few meters, compared its position after 20 years (Figure 4-28). This shows the system is reaching a thermal equilibrium. Thermal dispersion, in particular the dispersion through the solid matrix, has nearly stabilized for the thermal and hydraulic gradients.
Figure 4-29. Subsurface thermal profile of 10 m spaced BHE field with upgradient field effects after 30 years of operation.

To more accurately determine the temperature change over time, temperature values over time were recorded from a point in the center of the field at 45 m depth (Figure 4-30). We can see a rapid increase in temperature as the BHE system equilibrates with the subsurface, but a flattening of the curve around 15 years. The temperature increase between 20 and 30 years is about 0.3°C, a rather insignificant amount. For ease of comparison, difference plots for upgradient field can be seen in Appendix: E.
Figure 4-30. Internal temperature of downgradient BHE system at 45 m depth over 30 years.

The thermal plume’s 16°C isotherm (for both upgradient and downgradient fields) appears to extend laterally quite rapidly, but the 18°C isotherm remains relatively static (see Figure 4-25 to Figure 4-29). This may be due to the near balance of the system. The energy injection and extraction per year for the 10 m A and B systems were examined separately, as opposed to total energy extracted (see Appendix D). The injected energy was greater for the 10 m A system, however the energy extracted was greater for the 10 m B system. As the internal temperature of the BHE field increased due to the upgradient systems influence, the field was not able inject as much energy into the subsurface. However, the increased subsurface temperature meant that the energy extraction rate was higher, and more efficient. This may lead to the slow movement of the higher temperature plumes, as the balanced systems sets a thermal capacity on the temperature increase of the subsurface.
4.4.4 Constant operational cycle

The UWO geothermal system operates by alternating weekly between the BHE system and a horizontal system. Most BHE systems operate continuously and as such the effects of a continuously operating system were tested. The 10 m C system is active for the entire 20 year run of the simulation, as opposed to the 10 m A which is only operational for 50% of the time. The increased operational schedule effects on the subsurface are evident when viewed in cross-section (Figure 4-31). We can see that the internal BHE field is much warmer, averaging 16.2°C. This is almost 1°C warmer than the intermittent operational cycle. It is worth noting that the 10°C isotherm below the 10 m C BHE field exhibits the same upward inflection as seen in the 10 m A field (Figure 4-16). These are the result of the heating cycle’s influence within the first year of operation. These inflections are narrower below the 10 m C field, indicating that the continuous cooling cycle is having a greater impact on the subsurface than the intermittent cycle; despite the fact the continuous heating cycle likely would have drawn the 10°C isotherm further upwards than the 10 m A intermittent cycle. The size of the thermal plume is unchanged between the 10 m C and 10 m A fields.
Figure 4-31. Subsurface thermal profile of 10 m spaced BHE field with continuous operational cycle after 1 year of operation.

The 10 m C field continues to increase in temperature, as seen in Figure 4-32. The 18 °C isotherm has become prominent compared to the 10 m A field after 5 years. An average internal BHE field temperature was calculated by averaging the temperature of the nodes within the BHE field area for the entire length of the BHE system, with the nodes simulating the BHEs excluded. The internal field temperature of the 10 m C field is now 18.4°C, which is 1.3°C warmer than the 10 m A field. This is consistent with increased operation. It should be noted that the thermal plume expansion is not much greater for the 10 m C system. The 10°C isotherm beneath the 10 m C field is only about 2 m to 3 m deeper than the same isotherm below the 10 m A field.
Figure 4-32. Subsurface thermal profile of 10 m spaced BHE field with continuous operational cycle after 5 years of operation.

After 20 years of operation the thermal profile of the subsurface for the 10 m C field has become significantly different (Figure 4-33). We see the lateral expansion of the plume, exhibited best by the 14°C and 16°C isotherms, is closer in appearance to the 5 m A field plume (Figure 4-24) and the 10 m A field plume. While the plume has expanded greatly, the internal temperature of the field has not seen such dramatic growth, averaging 19°C. This is 1.1°C warmer than the 10 m A field after 20 years. For ease of comparison, difference plots for the constant operational cycle can be seen in Appendix: E.
Figure 4-33. Subsurface thermal profile of 10 m spaced BHE field with continuous operational cycle after 20 years of operation.

4.4.5 Extended BHE system

The extended BHE system uses the 10 m spacing and intermittent pumping cycle, but increases the length of the BHEs from 90 m to 150 m. The effects of the extended BHE system on the subsurface after the first year of operation can be seen in Figure 4-34. As one might expect, the extended BHE system has a deeper thermal profile than the 10 m A system. The first 90 m of the thermal plume created by the extended BHE system is very similar in size and even shape of the plume created by the 10 m A system. The internal temperature of the extended BHE system was found to be 14°C, 1°C cooler than the 10 m A system. The average of the first 90 m of the extended field was found to be the same as the 10 m A, and this was true for all time periods.
Figure 4-34. Subsurface thermal profile of 10 m spaced BHE field, with BHEs extended to 150 m, after 1 year of operation.

After 5 years of operation the thermal plume created expanded, and we can see a similar pattern to the 10 m A system at this time, only more elongate (Figure 4-35). The lateral expansion matches that of the 10 m A field. The extended BHE field has an internal temperature average of 16.1°C, which is 0.7°C cooler than the 10 m A field.
Figure 4-35. Subsurface thermal profile of 10 m spaced BHE field, with BHEs extended to 150 m, after 5 years of operation.

The subsurface thermal plume of the extended BHE system can be seen in Figure 4-35. The lateral expansion exhibited by the 16°C and 14°C isotherms seen at 215 m elevation are nearly identical to those of the 10 m A field after 20 years. The internal temperature of the BHE system is 17.1°C, and is half a degree cooler than the 10 m A BHE system. The average internal temperature of the extended system is cooler due to the extended gradient, and the decreasing temperature difference between the extended BHE field and the 10 m A field. The average internal field temperatures of the upper 90 m of the extended field are identical to the 10 m A field internal temperatures for all time periods. Even the shape of the extended field appears to be an elongate version of the 10 m A field, even after 20 years. Given the same operational parameters, the thermal influence of a field of a given length can be expected to behave similarly when BHE length is extended. For ease of comparison, difference plots for the extended BHE length can be seen in Appendix: E.
Figure 4-36. Subsurface thermal profile of 10 m spaced BHE field, with BHEs extended to 150 m, after 20 years of operation.
Chapter 5

5 Discussion

5.1 BHE energy exchange

5.1.1 Active BHE System: Actual vs Modeled

The modeled active BHE system had a significantly higher energy exchange than the actual active BHE system. A review of the data from enteliWEB, the geothermal system’s monitoring software, showed that data is recorded every 30 minutes, resulting in 48 records per day. This should result in 9,552 records for the 199 active days, however only 5,466 records were available. This means that the data set is only 57% complete. The energy total calculated from the recorded data was 87,541 MJ, while the simulated energy output of 160,059 MJ. When compared the calculate energy output is shown to be 54% of the simulated energy output. This similar ratio in missing data may be the cause of the energy output discrepancy between recorded and simulated energy output.

The missing data may be an error in recording, or retrieval of data. As stated in chapter 3.3.1, the operational cycle of the model assumes a steady 7-days-on, 7-days-off, as per HVAC engineering specifications. However, the system also operates “If return water temperature is greater than 18 °C, or lower than 10 °C…” (Larkin, 2018), which would mean it would be inactive during periods that did not meet the prescribed criteria. In which case, a simple 7-days-on, 7-days-off may overestimate, or underestimate energy output, depending on the weather for a given year. The 7-days-on, 7-days-off cycle should be effective over time as a year with fewer active days should be offset by a year with more. The recorded data available was for a 14 month period. It should also be noted that the goal of the study was to use actual recorded data to create the simulations, and not to simulate the active system.
5.1.2 BHE Fields

As one might expect, the BHE fields with the tightest spacing, and thus most boreholes, produced the most energy. The systems with the larger spacing produced less energy, but had higher energy exchange ratio, and thus being more efficient. The question becomes, is the increase in energy exchanged worth the decrease in efficiency? To be accurate this necessitates an estimate of a building’s energy requirements, and is discussed later in the chapter. But in broad terms we can compare the energy exchanged and energy exchange ratios of the spacings. From the second year of operation to the 20th year the 5 m A system’s energy exchange ratio goes from 97.2% to 95.2%, for an average of 95.6% efficiency over time. The first year is the maximum energy exchanged and represents 100% energy exchanged; as such it is not included when calculating the average decrease in energy exchange ratio.

The 10 m A, by comparison had an energy exchange ratio from 98.1% to 95.2%, for an average of 95.8% efficiency over time. An increase in efficiency of 0.2% over the 5 m A system. This means that for a 0.2% reduction of peak energy exchange, the total energy exchange can be increased by more than 3.5 times.

After deciding on the most effective spacing, the operational cycle is the next consideration. The 7-day cycle, as mentioned previously, is due to the BHE system sharing duties with a horizontal geothermal system. The more common operational cycle is a continuous one, where the system cycles the BHE fluid and changes the inlet temperature only. However, the 7-day cycle allows for thermal recovery of the subsurface, and has the potential to be more efficient. The energy exchange ratio for the continuous system (10 m C) ranges from 97.2% to 94.2%, an average of 95%. By comparing the 10 m A system’s energy exchange ratio to the 10 m C, we notice that the 10 m A is 0.8% higher. However, the 10 m C system exchanges an average of 2,522,958 MJ annually, 1.75 times the annual average of the 10 m A system. This, as previously mentioned, is not unexpected as the 10 m C system operates for twice the number of days per year as the 10 m A.

The 7-day cycle, while producing far less energy in comparison to the minor increased efficiency, did have a substantially smaller thermal plume develop over time (Figure 4-22). The upgradient systems tested in this study (discussed later in the chapter) operated on the 7-day
cycle. The upgradient systems were found to have little effect on the total energy exchanged after 20 and even 30 years of operation. This may be due to the intermittent operation that allows for thermal recovery of subsurface. A comparison of the effects of an upgradient system with a continuous operational cycle on a downgradient system to that of the 7-day cycle should be considered for future study.

In addition to changing the operational cycle, a large increase in energy can come by extending the length of the BHEs of a system. In this study the length was increased by 60% to 150 m. The extended system had the largest drop in energy exchange ratio, from 97.5% in the second year to 94.0% in the last, with an average of 94.8%. Compared to the 10 m A system this is a 1% loss of efficiency. However, the extended system’s annual energy exchange was 2,196,180 MJ, about 1.5 times larger than the 10 m A. The change from a 10 m A style system to a 10 m C would result in increased operational costs due to constant pumping, as opposed to running the pumps for 26 out of 52 weeks a year. And a change from a 10 m A to a smaller spacing would result in additional drilling costs. Extending the BHE length would increase both the drilling costs and the operational costs, as the increased length would increase drilling depth and energy required to cycle the BHE fluid.

All spacings and scenarios appear to have little variation in operational efficiency. This can be seen in the energy exchange ratio as well as the energy per BHE. For systems with tighter spacings, one would expect more substantial thermal interference, and while thermal plumes and internal temperatures seen in cross-section appear to show greater differences between the systems, the efficiency of the systems are not affected. This appears to be due to the nearly balanced system. The total annual energy exchanged is the sum of the energy injected as well as the energy extracted from the subsurface (see Appendix D). As the energy exchange total per year decreases, so does injected energy per year. However, the energy extracted per year increases each year. The extracted system becomes more efficient each year to take advantage of the increased subsurface temperatures. While the system is not perfect, it is able to minimize the efficiency lost by the cooling dominated system.

The active BHE system is supplemental to the overall heating and cooling needs of the CMLP building. A goal of this study was to determine how effective BHE fields would be in tight
building clusters and the effect of the surrounding infrastructure. To this end the findings of the BHE field tests were compared to determine which system would be able to best supply the CMLP’s heating and cooling needs. The energy requirements were estimated in chapter 4.1.2, and calculated the annual average energy requirements of the CMLP to be 9,642,579 MJ. This would require the system with the highest energy exchange, the 5 m C system at 9,740,499 MJ, to be installed. The energy calculations for the CMLP did not include the energy required for the building’s cooling system, meaning that the 5 m C system would still require supplementation. The CMLP building is also cooling dominated, so the energy requirements for the cooling system are likely to exceed that of the heating system. We can see that planning a geothermal system for the building would require more than a single field, or an expanded area.

5.1.3 Upgradient Fields

The addition of an upgradient field was studied to determine the effects on downgradient energy exchange. The energy exchange ratios showed that the addition of an upgradient field had no effect on the system for the first 5 years of operation. This represents the time required for the thermal influence of the upgradient system to reach the downgradient field in the model. After 5 years we saw a drop in the energy exchange ratios between the 10 m A field and the 10 m B field. However, the 10 m B field had an average energy exchange ratio of 95.4%, only 0.4% less than the 10 m A system which had no upgradient field to contend with. After 20 years the internal field temperature of the 10 m B field was only 0.7° warmer than the 10 m A. To see if the effects of the upgradient system would increase after 20 years, an additional 10 years was added to the model run and raised the internal downgradient temperature by 0.3°C and saw little expansion of the high-temperature isotherms from the upgradient systems. The 10 m spacing models did have a much smaller thermal plume than the 5 m spaced models, but they both showed very similar operational efficiency. It may be that the nearly balanced system prevents large plumes to travel much beyond the BHE field, and the temperatures that do reach downgradient systems are not sufficiently hot to cause more than a small drop in energy exchanged. This is dependent on the groundwater velocity and increased groundwater flow may move thermal plumes further and faster.
5.1.4 Effects of Infrastructure on BHE Energy Exchange

During sensitivity analysis, a variation of the 10 m A (10 m spaced model with the 7-on-7off schedule) was run, but infrastructure was not included in the spin-up of the model or the BHE field model. The model without infrastructure was run initially in steady state, and then converted to a transient model just as the 10 m A was, with the absence of infrastructure being the only difference. This was done to see what effects (if any) the infrastructure would have on the BHE energy exchange. The 10 m model without infrastructure was found to have an average annual energy exchange that was 2% higher than the original 10 m spaced model. There were other additions to the model that added additional complexity, such as the unsaturated zone, groundwater flow, even the monthly climate variations. Separate versions of the model were tested to determine the overall effect of each variable on BHE energy exchange values. Additionally, a 45 m length BHE model was run as well to determine if the subsurface heating effects were mitigated by the length of the original BHE model. All simulations had similar results, showing that removing the infrastructure, even with BHEs of 45 m length, did not have an appreciable effect on the energy exchanged.

In terms of estimating the energy exchanged it was shown that accurately modeling infrastructure and the resulting increased temperature of the subsurface, did not have any appreciable difference compared to a simple spin-up. While the inclusion of infrastructure has little effect on the actual BHE energy exchange outcome, it was a necessary step for the modeling process, namely for calibration. Field data could not be properly matched without the intensive spin-up process.

5.2 Subsurface Thermal Effects

The BHE system is cooling-dominated, and as such will inject more heat into the subsurface than is extracted. This can be seen in the balance plot and by the increase in temperature of the subsurface during the operational period of the BHE system during simulation.
The BHE spacing had the greatest effect on the internal BHE field temperatures, and the thermal plume created by the field. The tighter spacings, which had a higher BHE count for the given area, had the highest internal field temperatures and the largest thermal plumes. The same trend was seen between the operational cycles. As the continuous cycle doubles the annual operational days of the system, the internal field increases in temperature compared to the 7-day cycle.

As mentioned above, the upgradient BHE field did affect the CMLP field over the 20 year model run; however, the resulting temperature increase was small. We did see that the upgradient field does have a significant effect on the subsurface; however, the thermal plume traveled slowly. The 16°C isotherm appeared to combine between 5 and 10 years. This is when we begin to see a decrease in the energy exchange ratio for the 10 m B field compared to the 10 m A. We see the presence of the 16°C isotherm developing upgradient at 5 years, and the isotherm has progressed nearly 20 m after 10 years. We also see an 18°C isotherm developing after 20 years, but has expanded by no more than 4 m when the model is run for 30 years.

The extended BHE system had a very similar subsurface thermal profile compared to the 10 m A. The extended system’s thermal influence extended much deeper of course, but had the same lateral extent. For systems where, thermal influence of downgradient systems is an issue, extending the length of BHEs may be a possible solution. A possible example may be a design of a system in a limited area that, for environmental reasons, could have a thermal plume that had a lateral extent no larger than that of the 10 m A system, but required more energy. In that case extending the BHE length would maintain a sustainable thermal profile while increasing the annual energy exchange total.

5.3 Limitations and Uncertainty

All numerical models inherently have strengths and weaknesses and it is important to identify the sources of error and uncertainty. During the modeling process, many simplifications and assumptions had to be made. This is often the case for modeling in the subsurface. The main source of error for the model was the subsurface parameters. During sensitivity analysis it was
found that the parameter with the greatest effect on the subsurface temperature was the hydraulic conductivity. The hydraulic conductivity had the greatest range of values of all the parameters, often several orders of magnitude. The bedrock was given a single value for hydraulic conductivity, as the lithologic units were similar geologically. Additionally, each lithology has a range of hydraulic conductivity values within an order of magnitude. The values were also determined from regional scale reports from neighboring counties. The hydraulic conductivities used in the model have the highest uncertainty as they are estimated from a large range, and from regional sources. Sensitivity analysis was carried out to test the possible extremes of the hydraulic conductivity (see Appendix: E). Simulations were completed where the hydraulic conductivity was doubled and halved and the energy exchange values were compared to the 10 m spaced, 7-on-7off BHE system. It was found that when the hydraulic conductivity was doubled there was a 7% increase in energy exchanged. When the hydraulic conductivity was halved there was a 4% decrease in energy exchanged.

The thermal conductivity was shown to have some influence on the model outcomes, however not as substantial as the hydraulic conductivity. Thermal conductivity values came from a borehole study performed on the UWO campus. The borehole study is considered very accurate and high confidence was given to the values.

Surface parameters were also important to subsurface modeling accuracy. The two main parameters were the ground cover and the infrastructure. Ground cover was found to have a large impact during initial model builds. Ground-surface temperature had to be determined for grass cover as well as asphalt and concrete. The ground-surface temperatures were estimated using an equation relating air temperature to ground temperatures. The equation had been devised for St. Paul, MN, and not London, ON, however the climates of the cities are similar as are building materials used in road construction. The equation was used with climate data from London, ON and is presumed to be reasonably accurate. Infrastructure, which includes buildings and sewer systems are also sources of uncertainty. Both buildings and sewers were represented as constant temperature boundaries. The temperatures for building basement-ground boundaries were not measured, and were determined through sensitivity analysis based on literature values. The sewer temperature was based on literature values, as well as average annual temperatures of sewage
entering a near-by waste treatment plant. Both parameters were found to have moderate influence down to 90 m, and significant influence to 45 m. The spin-up steps showed that the omission of a single building over time will have a significant effect on the subsurface calibration. This is important as neglecting even a single building will show a cooler subsurface and improper thermal gradient. While the construction of the thermal profile was necessary for model calibration, it must be reiterated that the effects of infrastructure had little impact on the energy exchange values for the BHE systems. There is a high degree of confidence in these values.

The hydraulic head boundary conditions are considered another source of error for the model. Head boundaries for the model were estimated in part from regional reports and further refined based on topography of the model area. The reports were used to find an average gradient which was applied to the length of the model and the head difference calculated. Calculating the average gradient was done using reports from neighboring counties and may not wholly represent the model area. Sensitivity analysis was carried out to test the possible extremes of the hydraulic head differences (see Appendix: E). Simulations were completed where the hydraulic head difference was doubled and another where it was halved. The energy exchange values for the high or low head differences were compared to the 10 m spaced, 7-on-7off BHE system. It was found that the increased and decreased head difference models had a 7% increase and 3% decrease in energy exchanged respectively.

The field data relied on thermistors in monitoring boreholes attached to tubing at specified intervals and inserted to the boreholes. The thermistors were well calibrated prior to insertion and were attached correctly. The readings, as noted during calibration, from the thermistors had some fluctuation at depth, but were nearly identical at 90 m and 30 m. It is likely thermistors in one or more boreholes were shifted from the proper depth and are recording temperatures at the wrong depth. Several of the thermistors began to give anomalously low readings after some months, and it was determined that they had been compromised. The addition of an access tube to the thermistor boreholes was one possible solution; however, this would make the borehole subject to Ontario well regulations and add additional cost and complications beyond installation. These failed thermistors were easy to identify as well as the time of failure and they
did not affect the temperature results, beyond an unfortunate lack of data. Overall, the field data, omitting failed thermistors, is considered acceptable data.

Regarding the BHE system, there are also uncertainties. The enteliWEB monitoring system only allowed for retrieval of inlet/outlet temperature and pumping rate data for 12 to 18 months. This meant that inlet temperature was estimated from a relatively narrow window of time compared to the actual operational time of the model. Additionally, the operational cycle also responds to outdoor temperatures, and the narrow timeframe from which data was retrieved may also affect the accuracy of the inlet temperature. The pumping rate, however, appears to stay consistent during times of operation. The inlet temperature is considered to be of lower confidence, while the pumping rate has inherently less fluctuation and is considered to be of high confidence.

The model’s system solver utilized a single iteration with a decreased error tolerance to run the BHE field simulations. To ensure these simulations were accurate, a 100 day model was run using an increased error tolerance and ran with three iterations, based on the 10 m spacing, 7-on-7-off model. The results were compared to the 10 m model’s first 100 days to determine the energy exchange difference. It was found that there was a 2.9% variation in the energy exchanged between the simulations (see Appendix: E), with the slight overestimation being in favor of the single iteration model.
Chapter 6

6 Conclusions and Future Work

6.1 BHE Field Design Conclusions

The goal of this study was to provide a framework for the design of geothermal systems in tight urban environments with limited area for development of BHE fields.

When designing a BHE system, buildings, groundcover, and other infrastructure were found to have little effect on the BHE energy exchange, with only a 2% decrease in energy exchange when infrastructure was modeled. Modeling of the unsaturated zone was also found to have little effect as well, with a 3% decrease in energy exchange when the infrastructure and unsaturated zone was modeled. Accurate addition of infrastructure over time was found to be necessary to create an accurately modeled subsurface only during calibration. Simulations that do not include infrastructure or the unsaturated zone will increase the energy exchange values of BHEs, but only by 2% or 3%. It should be noted that removing groundwater flow from the model resulted in a 16% decrease of energy exchanged compared to a model that included groundwater flow as well as unsaturated zone and infrastructure. While infrastructure and the unsaturated zone have little overall effect the groundwater flow has a significant impact.

The nearly balanced nature of the BHE systems tested showed that the efficiency is retained to acceptable levels over time. This allows for tighter spaced BHE fields, which in turn exchange larger amounts of energy. Larger spacings may be more advantageous in situations where the system balance is skewed more to either heating or cooling. The 7-day cycle was found to increase efficiency, but as with the field spacing, this increase was limited due to the nearly balanced system. The continuous operational cycle was found to exchange more energy for a small reduction in efficiency, and would be much more suitable. The addition of an upgradient BHE field was found to impact an existing downgradient field; however, it was also very small. The internal field temperature was increased compared to a single field, but by a fraction of a
degree. Energy exchange was lower, but only by a small percentage. Provided a system is balanced or near balanced, A BHE field with 5 m spaced BHEs, and continuous operational cycle would be the most effective system. An upgradient field would not have a sufficient effect on the downgradient field’s internal field temperature, or the energy exchanged.

6.2 Future Work

(1) Further testing of an upgradient system effects on downgradient systems, specifically the distance and groundwater flow velocity. Future work may determine a minimum distance and/or groundwater flow velocity between fields. A minimum distance between BHE fields based on groundwater flow characteristics would assist with future BHE field placement.

(2) Balancing of building heat loads. Modern buildings are largely cooling dominated, and will always be nearly balanced at best. It may be beneficial to have two or more smaller independent fields that are themselves imbalanced, but together operate to balance the building heating and cooling loads.

(3) Testing optimal design and operation of the geothermal systems via a cost benefit analysis.
References


Ferguson, Grant, and Allan D. Woodbury. "Urban heat island in the subsurface." *Geophysical research letters* 34, no. 23 (2007).


Koepke, W.F., 1963, Well Name: University of Western Ontario No. 4. London ON, Canada: Department of Mines and Technical Surveys.


# Appendices

## Appendix A: Borehole Logs

**UWO No. 4 – 1963**

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**OPERATOR:**

Dept. of Mines & Technical Surveys, Ottawa

**TOTAL DEPTH:** 1948' UWO No. 4 – 1963

**GEOLOGIST:**

W.F. Koepke

**COORDINATES:**

860' E.

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**CAPPING AND TUNING RECORD:**

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**INTERVAL:**

- GLYPTOPORT
- ROCHESTER
- RHENGEQUIT
- RENHEAUX
- THORCOT
- GRUMSBY
- CAROT HEAD
- MANITOURIN
- WHIRLPOOL
- QUEENS
- ARAPORN - DUNDRE
- COLINGWOOD
- COORING
- BERTON
- BLACK RIVER
- ELGIN
- CARIBBEAN
- PIQUAMBAEAN

**TOTAL DEPTH (SAMPLES):**

1948

**FUEL RESULTS:**

1* Core at University of Western Ontario - Longon, Ont.
2 Rotary Rig (Diamond Drill)
3 Hole cemented at 130 - 180 ft. and 300 - 395 ft.

**PRESSURE:**

EXHIBIT 1
107
**Well Record**

**Regulation 351 Ontario Water Resources Act**

**Ontario Ministry of the Environment**

### Well Information
- **Well Number:** A025861
- **Province:** Ontario
- **Municipality:** City of London

### Well Owner's Information and Location of Well Information
- **First Name:** SISTERS OF ST. JOSEPH
- **Last Name:** Nuns
- **Address:** 1030 Richmond St., London, Ontario, N6A 5C7

### Log of Overburden and Bedrock Materials

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### Test of Well Yield

- **Pumping rate:** 104.5 gpm (gallons per minute)
- **Pumping time:** 15 minutes
- **Final water level:** 100.3' (feet below ground level)

### Construction Record

- **Casing Diameter:** 119'
- **Screen Diameter:** 0.188' * 3

---

*Sisters of Saint Joseph Borehole log*
## Subsurface Profile

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<td>4.05</td>
<td>Brown clayey silt, trace of sand &amp; gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.25</td>
<td>Grey clayey silt, trace of sand &amp; gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.75</td>
<td>Sand &amp; gravel (estimated max. pump rate 5 g.p.m.)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.25</td>
<td>Grey clayey silt till</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.65</td>
<td>Sand &amp; gravel (estimated max. pump rate 16 g.p.m.)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.65</td>
<td>Grey clayey silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.65</td>
<td>Grey clayey silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.65</td>
<td>Grey clayey silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.95</td>
<td>Grey clayey silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.95</td>
<td>Grey clayey silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.95</td>
<td>Grey clayey silt, increasing gravel content with depth</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.95</td>
<td>Grey to tan fractured limestone (pump test = 75 g.p.m.)</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.95</td>
<td>Open hole</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**WELL CONSTRUCTION**
- Bentonite seal
- 150mm diameter steel casing

**GROUND WATER**
- Type: 
  - 1: sand
  - 2: silt
  - 3: clayey silt
  - 4: sand & gravel
  - 5: grey clayey silt
  - 6: grey clayey silt, increasing gravel content with depth
  - 7: grey to tan fractured limestone

**VOC PIP**
- 0.5mm screen

**DATE:** June 18, 2005

**LOCATION:** 485 Windermere Road, London

**CLIENT:** Cornerstone Architecture

**PROJECT:** SSJ Residence

**DATUM ELEVATION:** Geodetic
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Material/Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>200.5</td>
<td>Grey to tan fractured limestone (pump test = 75 g.p.m.) (continued)</td>
</tr>
<tr>
<td>201</td>
<td>15 ga</td>
</tr>
<tr>
<td>202</td>
<td>16 ga</td>
</tr>
<tr>
<td>203</td>
<td>17 ga</td>
</tr>
<tr>
<td>204</td>
<td>18 ga</td>
</tr>
<tr>
<td>205</td>
<td>19 ga</td>
</tr>
<tr>
<td>206</td>
<td>20 ga</td>
</tr>
<tr>
<td>207</td>
<td>21 ga</td>
</tr>
</tbody>
</table>

End of Borehole 91.4 metres
UWO BHE and monitoring borehole drilling log

Timeline

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friday May 13th</td>
<td>The first of five wells was dug, the heating loops were installed with the thermistor, and it was grouted.</td>
</tr>
<tr>
<td>Saturday May 14th</td>
<td></td>
</tr>
<tr>
<td>Sunday May 15th</td>
<td></td>
</tr>
<tr>
<td>Monday May 16th</td>
<td>The second hole was dug and installed with heating loops and thermistor.</td>
</tr>
<tr>
<td>Tuesday May 17th</td>
<td>The second well was grouted and shortly after the crew started to experience problems with their gear box.</td>
</tr>
<tr>
<td>Wednesday May 18th</td>
<td>Drilling was on hiatus due to equipment difficulties.</td>
</tr>
<tr>
<td>Thursday May 19th</td>
<td>Drilling was on hiatus due to equipment difficulties.</td>
</tr>
<tr>
<td>Friday May 20th</td>
<td>Drilling was on hiatus due to equipment difficulties.</td>
</tr>
<tr>
<td>Saturday May 21st</td>
<td></td>
</tr>
<tr>
<td>Sunday May 22nd</td>
<td></td>
</tr>
</tbody>
</table>
Soil observations

I was able to acquire soil samples from well 2 at 30ft, 40, 50, 80, 108, 120, 140, 160, 180, 200, 220, 240, 260, 280, and 300. Also, I was able to get samples from well 3 at 10ft intervals from 10ft – 110ft. It can be observed in the soil samples that there is primarily clay from 10ft – 60ft. At 60 ft there seems to be more gravel mixed with the clay. From 110ft the bedrock starts and continues until the bottom of the well at 300ft. According to the drillers the bedrock was mostly limestone with perhaps some dolomite. Also, the rock seemed to be fairly consistent and whenever I asked about the quality of the limestone I was told that they hardly encountered any significant fractures (few inches of discontinuity). Lastly, they used the same type of tubing used in the heating loops to insert the thermistors in wells 3-5.
Grout

In well 1 they used Benseal to grout the outside of the heating loops, and in all of the other wells they used a different mixture with silica sand, water, and Berotherm. I have also included a picture of the type of sealant used in the top of wells 3-5.
Appendix B: Regional Equipotential Maps

All maps taken from Dillon Consulting and Golder Associates Ltd. (2004).
Appendix C: Description of Actual BHE System Energy Calculation

Energy produced by active BHE system was calculated from a one year period from April 4th, 2017 to April 3rd, 2018. This period was chosen as it had available inlet and outlet temperature data with corresponding pumping rates. The pumping rate was required as the inlet and outlet temperatures recorded by enteliWEB are continuously and not only when the vertical system is operational. This time period saw 199 active days.

To calculate total energy for a given period, it was recommended to calculate power as done by CLMP HVAC engineering, then convert power into energy for the given time period (Larkin, 2018).

Temperature difference was used to calculate power, using an equation;

\[
Power = (Pumping \ rate) \times |(Inlet \ temperature - Outlet \ Temperature)| \times 1.8 \times \frac{478}{1000}
\]

This resulted in kilo British Thermal Units per hour (kBTU/hr), which was converted to energy (kilo British Thermal Units) by simply multiplying the power by the 30-minute recording period. Finally, kBTUs were converted to mega joules (MJ), as this made it easier to compare data with FEFLOW simulated data, which uses metric values for energy.
Appendix D: Injection and Extraction Ratio

Table A 1. Example of energy per year injected and extracted as well as total. For 5 m A scenario.

<table>
<thead>
<tr>
<th>Year</th>
<th>Energy per year injected (MJ)</th>
<th>Energy per year extracted (MJ)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,070,633</td>
<td>1,458,056</td>
<td>5,528,688</td>
</tr>
<tr>
<td>2</td>
<td>3,384,279</td>
<td>1,991,969</td>
<td>5,376,248</td>
</tr>
<tr>
<td>3</td>
<td>3,178,443</td>
<td>2,148,279</td>
<td>5,326,722</td>
</tr>
<tr>
<td>4</td>
<td>3,096,134</td>
<td>2,210,465</td>
<td>5,306,599</td>
</tr>
<tr>
<td>5</td>
<td>3,054,288</td>
<td>2,241,719</td>
<td>5,296,007</td>
</tr>
<tr>
<td>6</td>
<td>3,029,128</td>
<td>2,260,323</td>
<td>5,289,451</td>
</tr>
<tr>
<td>7</td>
<td>3,012,251</td>
<td>2,272,687</td>
<td>5,284,938</td>
</tr>
<tr>
<td>8</td>
<td>3,000,086</td>
<td>2,281,509</td>
<td>5,281,595</td>
</tr>
<tr>
<td>9</td>
<td>2,990,868</td>
<td>2,288,112</td>
<td>5,278,980</td>
</tr>
<tr>
<td>10</td>
<td>2,983,633</td>
<td>2,293,227</td>
<td>5,276,860</td>
</tr>
<tr>
<td>11</td>
<td>2,977,796</td>
<td>2,297,295</td>
<td>5,275,090</td>
</tr>
<tr>
<td>12</td>
<td>2,972,975</td>
<td>2,300,591</td>
<td>5,273,566</td>
</tr>
<tr>
<td>13</td>
<td>2,968,927</td>
<td>2,303,306</td>
<td>5,272,233</td>
</tr>
<tr>
<td>14</td>
<td>2,965,472</td>
<td>2,305,575</td>
<td>5,271,048</td>
</tr>
<tr>
<td>15</td>
<td>2,962,487</td>
<td>2,307,491</td>
<td>5,269,978</td>
</tr>
<tr>
<td>16</td>
<td>2,959,872</td>
<td>2,309,125</td>
<td>5,268,996</td>
</tr>
<tr>
<td>17</td>
<td>2,957,562</td>
<td>2,310,530</td>
<td>5,268,091</td>
</tr>
<tr>
<td>18</td>
<td>2,955,498</td>
<td>2,311,747</td>
<td>5,267,245</td>
</tr>
<tr>
<td>19</td>
<td>2,953,642</td>
<td>2,312,810</td>
<td>5,266,453</td>
</tr>
<tr>
<td>20</td>
<td>2,951,956</td>
<td>2,313,743</td>
<td>5,265,699</td>
</tr>
</tbody>
</table>
Figure F 1. Comparison of injected, extracted, and total energy exchange ratios. Note how extracted energy increases much more than injected energy.
Appendix E: Sensitivity Analysis

Table A 2. Average annual energy exchange for increased and decreased hydraulic conductivity (K) and hydraulic head, as well as overall difference compared to 10 m A model.

<table>
<thead>
<tr>
<th>Model Run</th>
<th>Increased K</th>
<th>Lowered K</th>
<th>High Head</th>
<th>Low Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Average (MJ)</td>
<td>1,537,981</td>
<td>1,387,397</td>
<td>1,539,679</td>
<td>1,398,629</td>
</tr>
<tr>
<td>Percentage difference</td>
<td>+7%</td>
<td>-3%</td>
<td>+ 7%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

Table A 3. Comparison of energy exchange for 100 days between a single iteration and three iteration solver.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Energy exchange (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three iteration</td>
<td>448,664</td>
</tr>
<tr>
<td>Single iteration</td>
<td>461,591</td>
</tr>
</tbody>
</table>
Appendix F: Difference Plots

Difference plots for subsurface temperature change. All plots compare initial conditions (i.e. pre-BHE activation temperatures) to designated year of activity, unless otherwise stated.

5 m spacing, 7-on-7-off

Figure F 2. Difference plot comparing initial conditions to 1 year of operation.
Figure F 3. Difference plot comparing initial conditions to 5 years of operation.

Figure F 4. Difference plot comparing initial conditions to 20 years of operation.
10 m spacing, 7-on-7-off

Figure F 5. Difference plot comparing initial conditions to 1 year of operation.
Figure F 6. Difference plot comparing initial conditions to 5 years of operation.

Figure F 7. Difference plot comparing initial conditions to 20 years of operation.
10 m spacing, upgradient BHE system

Figure F 8. Difference plot comparing initial conditions to 1 year of operation.
Figure F 9. Difference plot comparing initial conditions to 5 years of operation.
Figure F 10. Difference plot comparing initial conditions to 20 years of operation.
10 m spacing, continuous operation

Figure F 11. Difference plot comparing initial conditions to 1 year of operation.
Figure F 12. Difference plot comparing initial conditions to 5 years of operation.
Figure F 13. Difference plot comparing initial conditions to 20 years of operation.
Curriculum Vitae

Name: Ronan Drysdale

Post-secondary Education and Degrees:
Carleton University, Ottawa, Ontario, Canada
2010-2014 B.Sc.

Related Work Experience:
Mining Geologist
Porcupine Gold Mines - Goldcorp
2014-2016

Teaching Assistant
The University of Western Ontario
2016-2018