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Characterizing long-term groundwater conditions and lithology for the design of large-scale borehole heat exchangers

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CHARACTERIZING LONG-TERM GROUNDWATER CONDITIONS AND LITHOLOGY FOR THE DESIGN OF LARGE-SCALE BOREHOLE HEAT EXCHANGERS

by

DAVID CHARLES SMITH

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PUBLICATION DISSERTATION OPTION

This dissertation has been prepared in publication format and consists of the following three articles that have been submitted for peer-reviewed publication as follows:

Paper I, Pages 22-42, is titled "The Effect of Seasonal Groundwater Saturation on the Effectiveness of Large Scale Borehole Heat Exchangers in a Karstic Aquifer," and was submitted to the Journal *Geothermics*.

Paper II, Pages 43-68, is titled "The Observed Effects of Changes in Groundwater Flow on a Borehole Heat Exchanger of a Large Scale Ground Coupled Heat Pump System," and was submitted to the Journal *Geothermics*.

Paper III, Pages 69-94, is titled "Characterizing Lithological Effects on Large Scale Borehole Heat Exchangers during Cyclic Heating of the Subsurface," and was submitted to the Journal *Geothermics*.

ABSTRACT

Construction of large scale ground coupled heat pump (GCHP) systems that operate with hundreds or even thousands of boreholes for the borehole heat exchangers (BHE) has increased in recent years with many coming on line in the past 10 years. Many large institutions are constructing these systems because of their ability to store energy in the subsurface for indoor cooling during the warm summer months and extract that energy for heating during the cool winter months.

Despite the increase in GCHP system systems constructed, there have been few long term studies on how these large systems interact with the subsurface. The thermal response test (TRT) is the industry standard for determining the thermal properties of the rock and soil. The TRT is limited in that it can only be used to determine the effective thermal conductivity over the whole length of a single borehole at the time that it is administered. The TRT cannot account for long-term changes in the aquifer saturation, changes in groundwater flow, or characterize different rock and soil units by effectiveness for heat storage.

This study established new methods and also the need for the characterization of the subsurface for the purpose of design and long-term monitoring for GCHP systems. These new methods show that characterizing the long-term changes in aquifer saturation and groundwater flow, and characterizing different rock and soil units are an important part of the design and planning process of these systems. A greater understanding of how large-scale GCHP systems interact with the subsurface will result in designs that perform more efficiently over a longer period of time and expensive modifications due to unforeseen changes in system performance will be reduced.

ACKNOWLEDGMENTS

Many have helped me through this long journey, and I owe them all a great deal of thanks. First, I would like to thank my advisor, Dr. Curt Elmore, who has encouraged and guided me through three degrees. He has been a great mentor, and I hope that I can mentor and encourage others through my career as well as he has done for me.

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1. INTRODUCTION

The emerging research on climate change and its ramifications has focused the attention of government agencies, academic institutions, and private industry to find ways to shift their reliance on fossil fuels to renewable sources of energy. The world currently relies heavily on the combustion of fossil fuels for energy needs which includes heating and cooling. The United States consumed approximately 80.4 quadrillion British Thermal Units (Btu) of fossil fuels in 2014. This accounted for 82 percent of the total U. S. energy consumption. The three largest sources of energy used in the U.S. in 2014 were petroleum (35 percent of the total U.S. energy consumption), natural gas (28 percent of the total U.S. energy consumption), and coal (18 percent of the total U.S. energy consumption; EIA, 2017).

Fossil fuels contribute to the release of the greenhouse gas, carbon dioxide (CO_2), into the atmosphere and have been traced back to the consumption of fossil fuels isotopically. Carbon that is depleted in carbon 14 (^{14}C) is a tracer for carbon from fossil fuels while carbon that is depleted in carbon 13 (^{13}C) is a tracer for both fossil fuels and for land use. Recent measurements of carbon in the atmosphere and in tree rings have shown that ^{14}C and ^{13}C have been diluted relative to carbon 12 (^{12}C) as CO_2 concentrations in the atmosphere have increased (Vitousek, 1997). CO_2 concentrations remained relatively stable at 180 parts per million (ppm) and 280 ppm for thousands of years until the 1800's as has been shown through the analysis of air bubbles from ice cores collected in Antarctica (Petit et al., 1999). Recent measurements of atmospheric CO_2 have shown that CO_2 concentrations have increased in the atmosphere from 315 ppm in 1957 (Vitousek, 1997) to 391 ppm in 2011(Stocker et al., 2014).

Many forms of renewable energy are currently being used including wind, solar, hydroelectric, biomass, and geothermal to lessen our dependency on fossil fuels (Turner, 1999). One form of geothermal energy application that has experienced incredible growth (Lund et al., 2004) is ground coupled heat pump (GCHP) systems. GCHP systems have increased in use 10 percent annually from 1994 to 2004 in about 30 countries.

1.1 REVIEW OF RELEVENT LITURATURE

GCHP systems use the subsurface to store or acquire heat energy due to its constant year round temperature. The effect of ambient outside air temperature diminishes with depth. The subsurface temperatures generally remain stable year round below 5 meters (m, Florides and Kalogirou, 2007). Heat is removed from indoors through the use of a heat pump in the warm summer months. The heat pump heats up water (antifreeze and water mixture in some cases) which is pumped through a ground heat exchanger. Heat is transferred from the water to the surrounding soil, rock, and water by conduction or advection. During the cold winter months, the process is reversed. Cool water is pumped through the ground heat exchanger where it acquires heat energy from the surrounding soil, rock, and water. That heat energy is then transferred to the indoors for heating (Florides and Kalogirou, 2007). This method is generally more effective than heat pumps that transfer heat energy from the outside air to the indoors or from indoors to the outside air. In the winter months, the outside air is typically cooler than the temperature of the ground therefore there is less stored energy in the air. In the summer months when heat is being removed from the building by the heat pump, the outside air is much warmer than the temperature of the ground therefore more energy can be stored in the ground.

The ground heat exchangers are constructed within the subsurface and circulate water for heating and cooling. There are generally two type of ground heat exchangers, closed-loop and open-loop systems.

Closed-looped systems do not allow mixing of the circulation fluid with groundwater. The circulation fluid is enclosed within the system and is circulated through pipes that are buried or installed in the ground. The pipes are generally made of high density polyethylene which is very durable. Mass (fluid) is not transferred with the ground, only energy by conduction.

Closed-loop systems generally have horizontal or vertical loops. The horizontal loops are generally near surface. A trench is excavated in which the pipes lay horizontally several feet below the surface. The pipes can be installed in several different designs such as in parallel, in series, and coil type as shown in Figure 1.1 (Florides and Kalogirou, 2007).

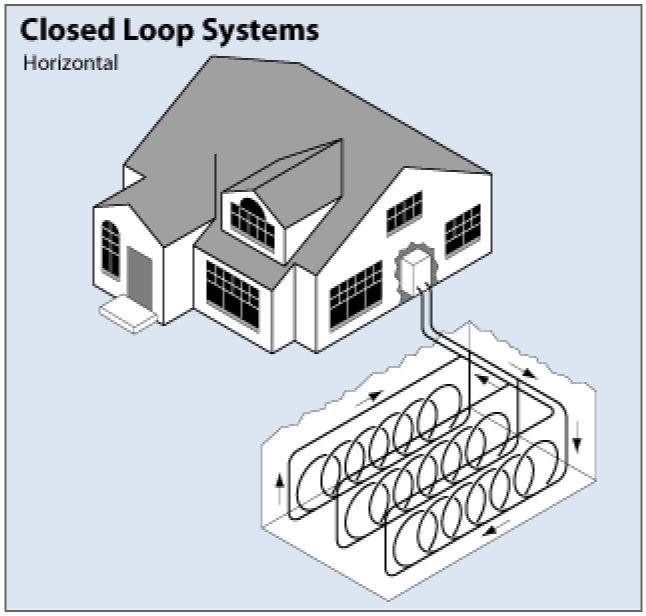

Figure 1.1 Horizontal closed-loop system (adapted from Department of Energy, 2017).

Vertical closed-loop systems typically extend much deeper into the ground than horizontal systems as shown in Figure 1.2. These systems generally extend into the deeper part of the subsurface that is less affected by ambient outside air temperature and is typically greater than 5 m (Florides and Kalogirou, 2007). Vertical closed-loop systems are commonly called borehole heat exchangers (BHE). A well is typically drilled to a certain depth. Then a u-tube made of high density polyethylene is installed into the borehole and grouted to the surface. Water can be circulated thorough the u-tube. Water is pumped through one side of the u-tube, flowing from the surface to the bottom of the borehole. The pipe has a u-shape at the bottom of the borehole which directs the water back towards the surface. BHEs are typically more expensive to install but require considerably less pipe due to the more stable temperatures deep in the subsurface. The deep subsurface greater than 5 m is generally warmer than the outside air in the winter and cooler than the outside air in the summer (Florides and Kalogirou, 2007).

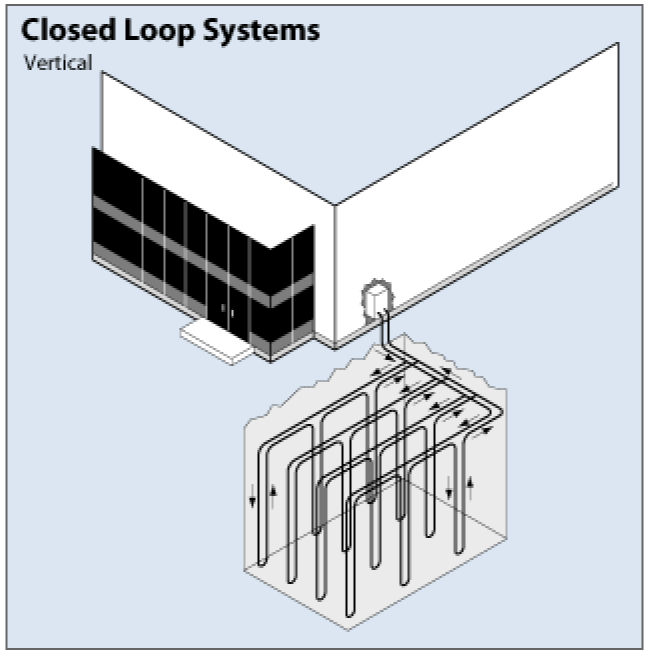

Figure 1.2 Vertical closed-loop system (adapted from Department of Energy, 2017).

Open-looped systems differ from closed-looped systems in that both mass and energy is exchanged with the subsurface. These systems generally pump water directly from the ground to cool heat pump coils in the summer or warm heat coils in the winter. This typically requires 2 wells with one as an injection well and one as an extraction well as shown in Figure 1.3 (Florides and Kalogirou, 2007).

The number of large-scale GCHP systems is increasing as the benefits of these systems become more evident. Stockton College in southern New Jersey completed a large-scale GCHP system in 1994. This BHE consisted of 400 boreholes each drilled to a depth of 130 m (Taylor et al., 1997). The boreholes extend through the Kirkwood-Cohansey aquifer system which is generally characterized as variable with interbedded layers of sands, gravels, and clays and is a principle unconfined aquifer system in the New Jersey Coastal Plain (Zapecza, 1989). Within the aquifer system is the Rio Grande water bearing zone at 96 to 107 m which was expected to have higher specific heat and thermal conductivity. The flow of groundwater was also expected to enhance heat transfer between the BHE and the aquifer (Taylor et al., 1997). The construction of the

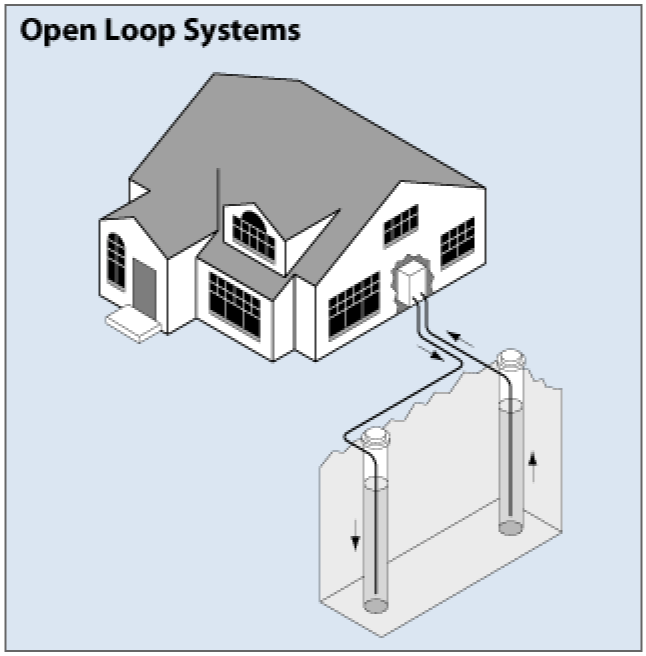

Figure 1.3 Open-loop system (adapted from Department of Energy, 2017).

system initially cost 5.1 million dollars but much of this was covered by grants and utility rebates. The annual savings of the system was $400,000 in fuel and maintenance costs which included a reduction in the use of electricity and natural gas and a large reduction in CO2 emissions (Cross et al., 2011).

Ball State University's (BSU) GCHP system went online in the spring of 2012 and is currently considered the largest in the nation. This system consists of 3,600 boreholes drilled to depths of 122 to 152 m deep. Indiana Department of Natural Resources well number 421719 was completed on December 23, 2009 on the campus of BSU. It was drilled to a depth of 122 m through 7 m of clay, 2 m of gravel, a second 9-m layer of clay, 43 m of limestone, and 61 m of shale (IDNR, 2009). The GCHP system heats and cools 47 buildings (511,000 m^2) on the 295 hectare campus which helped the university reduce CO_2 emissions by 77,000 metric tons annually by taking its fossil-fuel boilers offline (BSU, 2016).

The Missouri University of Science and Technology (S&T) completed a similar scale GCHP system in 2014 in an effort to reduce heating and cooling costs and water use. This paper describes the impact of seasonally variable water levels, or percent saturation, on the BHE system performance at one of the Missouri S&T GCHP subsystems. The BHE was installed in nearly 122 m of karstic dolomite and sandstone. A temperature monitoring well was installed adjacent to subject subsystem well fields and instrumented with thermocouples to monitor the overall temperature of the subsurface near the system. Similar instrumentation was installed in a production BHE well near the center of the BHE well field but was not referred to in this particular study. The effectiveness of the BHE was calculated using the temperature of the subsurface near the geothermal system, flowrate and temperature of the water in the closed-loop BHE as it entered the aquifer and as it left the aquifer. This effectiveness was compared to local aquifer saturation estimated from water levels in a nearby groundwater observation well. The S&T GCHP system is one of the largest systems of its kind in the United States. The system was designed to replace an aging heating and cooling system which had a nearly 70 year old power plant that provided steam using coal and woodchip fueled boilers. The GCHP system consists of 789 closed loop geothermal wells between 122 and 134 m deep. The BHE serves 3 primary campus GCHP plants and one satellite plant at the 42,178 m^2 Gale Bullman Multi-purpose Building. Each plant consists of heat recovery chillers (500 tons) and supplementary cooling towers and gas-fired boilers which help to heat and cool the campus buildings during extreme temperatures The new system allowed S&T to reduce annual energy consumption by 57 percent, CO_2 by 23,000 metric tons per year, and water usage by 85 million liters per year (S&T, 2016).

Many more institutions across the country that have implemented these large GCHP systems include Lake Land College in Illinois, Drury University in Missouri, Harvard University in Massachusetts, Feather River College in California, Hamilton College in New York, Northland College in Wisconsin, Yale University in Connecticut, and many more (Cross et al., 2011).

Despite the growing number of large-scale GCHP systems, only a small fraction of the construction budget is used for the characterization of the geohydrology or the long term monitoring of the system and its long-term effects on the aquifer (Florea et al., 2016).

Groundwater fluctuations of increasing or decreasing saturation may affect the thermal conductivity of the soil and rock surrounding the BHE. As the saturation of rocks with water increases, the thermal conductivity increases also (Clauser and Huenges, 1995; Robertson, 1988, Albert et al., 2016). Mohamed et al. (2015) constructed a bench-scale model of a horizontal ground heat exchanger. The model was constructed in a 1-m cubed box with a sandy soil surrounding the heat exchanger. Coolant was pumped through the ground heat exchanger with differing water levels in the soil and simulated precipitation. Mohamed et al. (2015) reported that heat transfer between the heat exchanger and soil was enhanced during simulated high water levels and precipitation events. While changes in water levels may reflect similar behavior in deep BHEs, similar behavior from precipitation events is less likely due to thick layers of low permeable materials near the surface.

Many studies have shown that groundwater flow affects the heat transfer between BHEs and the rock and soil (Chiasson et al., 2000; Lee and Lam., 2007; Fan et al., 2007). Chiasson et al. (2000) used a finite-element numerical groundwater flow and heat transport model to simulate groundwater flow and its effect on a single u-tube BHE in different types of soil and rock. Chiasson et al. (2000) demonstrated that groundwater flow generally had an effect on heat transfer in material with high hydraulic conductivity such as sands, gravels, and fractured rock. Simulated TRTs in the study generally produced artificially high thermal conductivity values when groundwater flow was present.

Lee and Lam (2007) used computer simulations of a GCHP system performance with different thermal loading profiles and different BHE shape configurations (width and length ratios of 1:1, 1:2, and 2:3) to compare the performance of each under groundwater flow. The square BHE configuration was less likely to be affected by groundwater flow direction as its width and length ratio is the same in all directions (Lee and Lam., 2007).

Fan et al. (2007) developed a dynamic mathematical model to account for groundwater advection and its effect on a BHE. The model showed that the groundwater significantly affected the heat transfer between the BHE and the surrounding soil. Different groundwater flow velocities also had a noticeable effect on the heat transfer between and its effect on a BHE. The model showed that the groundwater significantly affected the heat transfer between the BHE and the surrounding soil with simulations of groundwater velocities of zero, 15, 30, and 60 meters per year (m/yr), Fan et al. (2007)

reported that heat transfer between the BHE and surrounding soil increased with increasing groundwater velocity. Fan et al. (2007) concluded that groundwater flow should be considered in the design of GCHP systems.

Different types of lithology have been shown to have a range of thermal properties which can greatly affect the performance of BHE's. Robertson (1988), Siliski (2014), Albert et al. (2016), and Sass and Götz (2012) have shown that thermal properties can vary with rock type. Boring logs near BHEs for large scale GCHP systems generally extend through multiple rock or soil units that may have vastly different thermal properties. The boreholes at Stockton College extended through three different aquifers that were separated by layers of clay. The water bearing units were expected to have higher thermal conductivity and specific heat than the clay layers (Taylor et al., 1997). Boring logs from wells on the BSU campus show the wells generally extend through clay, gravel, limestone, and shale (IDNR, 2009).

The thermal response test (TRT) is the industry standard method used to determine the effective thermal conductivity of the surrounding rock and soil of a BHE (Florea et al., 2016). The test generally uses the Kelvin Line Source Theory to calculate the thermal conductivity by plugging in known parameters and parameters estimated from the inlet and outlet water temperature over time (Sanner et al., 2005). Water is generally circulated for a period of 48 hours at a constant temperature: an effective thermal conductivity value if the soil and rock within borehole is calculated with the TRT test. However, the TRT does not consider long-term changes in the saturation of the aquifer, groundwater flow, or the lithology (Diao et al., 2004; Siliski, 2014). Siliski (2014) compared the results of a TRT and the laboratory analysis of core samples from a site. The measured thermal conductivities of the cores were vastly different from that of the effective thermal conductivity of all the rock surrounding the borehole. Siliski (2014) reported that the TRT does not indicate what specific rock units transfer heat more effectively. Not fully characterizing the subsurface could result in future expensive retrofits. Sowers et al. (2006) reported that an additional 750 ton cooling tower was added to the GSHP system at Robert Stockton College in 2005 to bring the system into equilibrium because the aquifer was warming over time due to more heat being rejected in the summer than extracted in the winter.

1.2 STUDY AREA

The study area is located on the Missouri University of Science and Technology Campus in Rolla, Missouri as shown in Figure 1.4. The region is considered a prime candidate for GCHP systems due to hot summers and cold winters. This allows equal heating of the aquifer in the summer and cooling in the winter, preventing long-term warming or cooling.

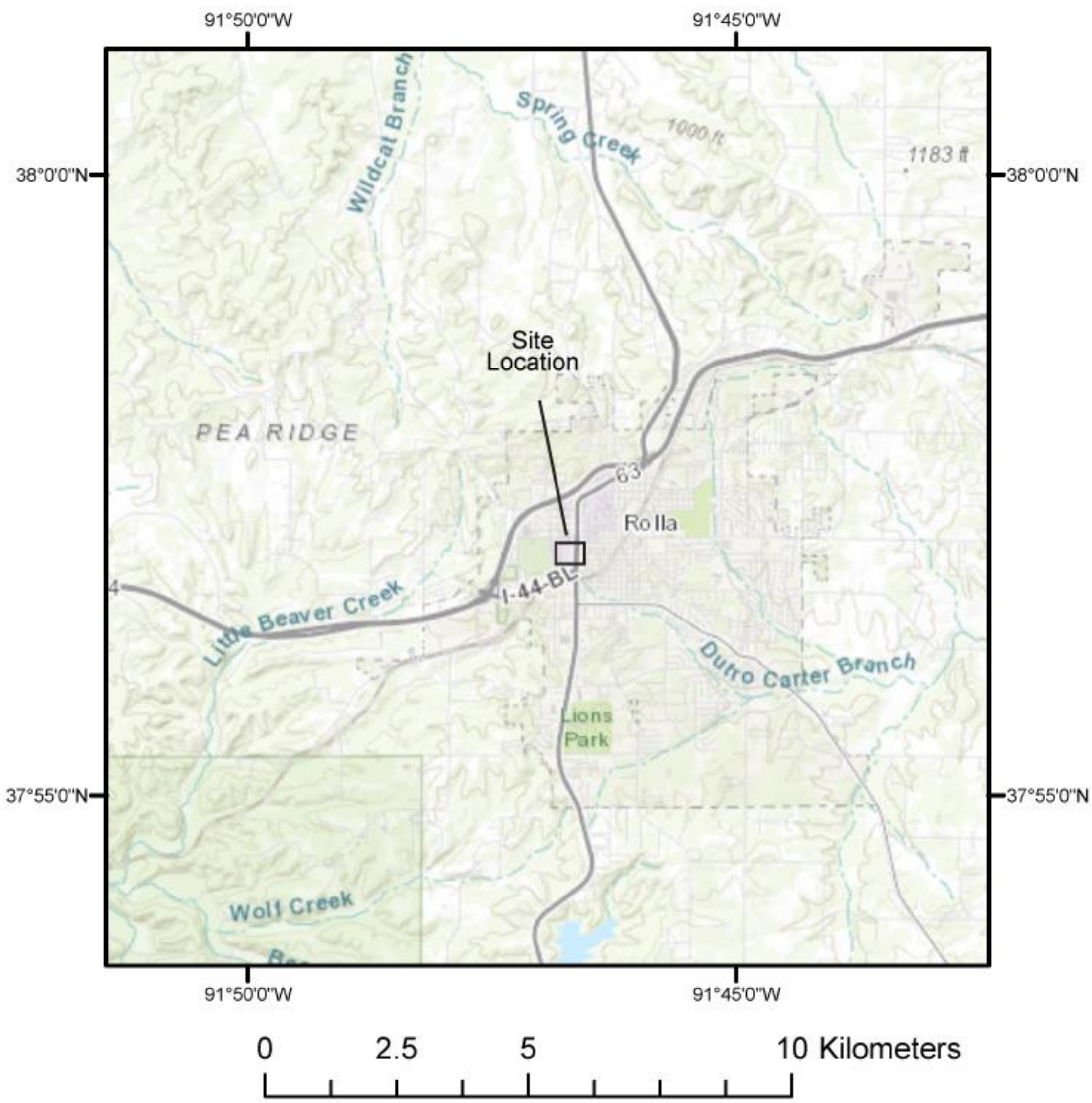

Figure 1.4 Map of the study area in Rolla, Missouri-2014-17.

The area is underlain by the Ozark Aquifer which generally consists of cherty dolomites and sandstones. The lithological units on the site that are part of the Ozark Aquifer are karstic formations which are the Cotter Dolomite, Jefferson City Dolomite, the Rubidoux Formation, the Upper and the Lower Gasconade Dolomite, the Eminence Dolomite and the Potosi Dolomite overlain by residuum. The overall thickness of these units at the site is typically 305 to 365 m thick (Vandike, 1992).

The Ozark Aquifer is a major source of water for private residence and municipalities for parts of Missouri, Kansas, Oklahoma, and Arkansas (Imes and Emmet, 1994, Vandike, 1992). Water is stored in the pores and in solution widened fractures of the rock. The Cottter and Jefferson City Dolomite are generally exposed at the surface. The Cotter Dolomite is typically very thin in the area if present and therefore is not a producer of water. Below the Cotter Dolomite is the Jefferson City Dolomite which produces modest amounts of water [less than 0.04 cubic meters per minute (m^3/min)]. Many of the older residential wells are open to this formation. The Roubidoux Formation is highly permeable and is a good producer of water. Many residential wells are open to this formation which can typically produce 0.04 to 0.15 m^3/min. The Upper Gasconade Dolomite is a low chert dolomite with relatively low permeability. It can be considered a leaky confining unit. The lower Gasconade Dolomite is generally a better producer of water than the Upper Gasconade Dolomite producing upwards of 0.28 to 0.47 m^3/min. Most municipal wells are open to the Upper Gasconade Dolomite, the Eminence Dolomite, and the Potosi Dolomite. These wells can produce 1.3 to 3.8 m^3/min (Vandike, 1992)

Missouri has a continental type climate that is characterized by strong seasonality. Cold and warm air masses are typically free topographically allowing cold air from the north to push south in the winter and warm moist air from the south push north in the summer creating relatively significant amounts of snow and rain. Winters are cold and summers are hot although because of its inland location, prolonged cold or hot or cold periods are rare (Decker, 2017).

The study site is home to one of the most recent large-scale GCHP systems in the country. S&T’s system went on line in 2014 and is the main heating and cooling system for the campus. The system replaced an aging nearly 70 year old power plant that provided steam using coal- and woodchip-fueled boilers which reduced the carbon dioxide emissions by 25,000 tons per year. It consists of three primary campus GCHP plants. The plants consist of heat recovery chillers (500 tons), supplementary cooling towers, and gas-fired boilers which help to heat and cool the campus buildings during extreme temperatures. The GCHP system plants are served by multiple BHE's with 780 production wells drilled to depths of 122 m to 134 m through karstic rock of the Ozark Aquifer making it geologically important for future research. Overall, the system has helped S&T reduce its energy consumption by 57 percent and water use by 85 million liters per year (S&T, 2016).

1.3 DATA COLLECTION

The 144 well BHE for S&T GCHPS satellite plant at the 42,178 m^2 Gale Bullman Multi-purpose Building is the focus of this study. A total of 16 thermocouples were installed in the center production well of the BHE. Thermocouples were attached at 15.2-m intervals on each side of the u-tube from 15.2 m to 400 m below the surface as shown in Figure 1.5. These thermocouples measured the temperature at the interface of the outside of the u-tube and the grout. An additional non-production well was drilled 6 m directly west of the BHE as shown in Figure 1.6. This is referred to as the temperature monitoring well. It was designed to measure the ambient subsurface temperature adjacent to the BHE. Thermocouples were attached at 15.2-m intervals on a single modified u-tube from 15.2 m to 400 m below the surface as shown in Figure 1.5. The modified u-tube was spliced at the bottom making it a single straight pipe rather than a loop. The thermocouples were operated by two Campbell Scientific CR10X dataloggers from August, 2015 through December, 2015 and by two Campbell Scientific CR10 dataloggers from January, 2016 through June, 2017. The dataloggers also record internal temperature with an onboard thermistor which is necessary for calculating temperature measured by the thermocouples. The dataloggers were housed in a concrete electrical box at the surface as shown in Figure 1.7.

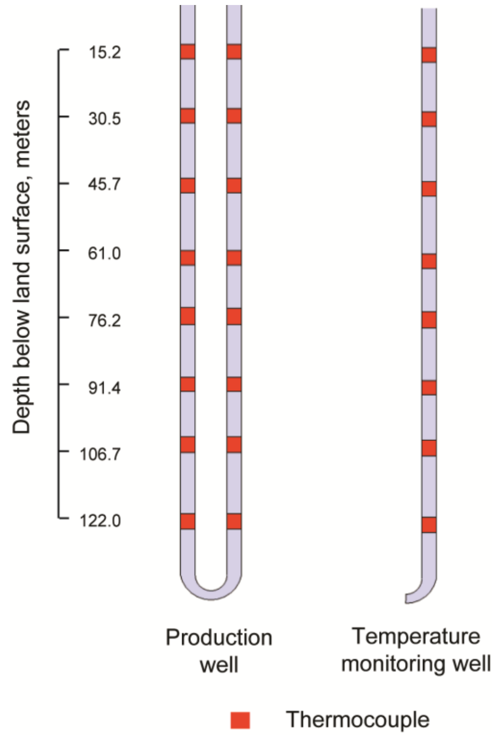

Figure 1.5 Illustration showing the thermocouple locations on the production well and the temperature monitoring well.

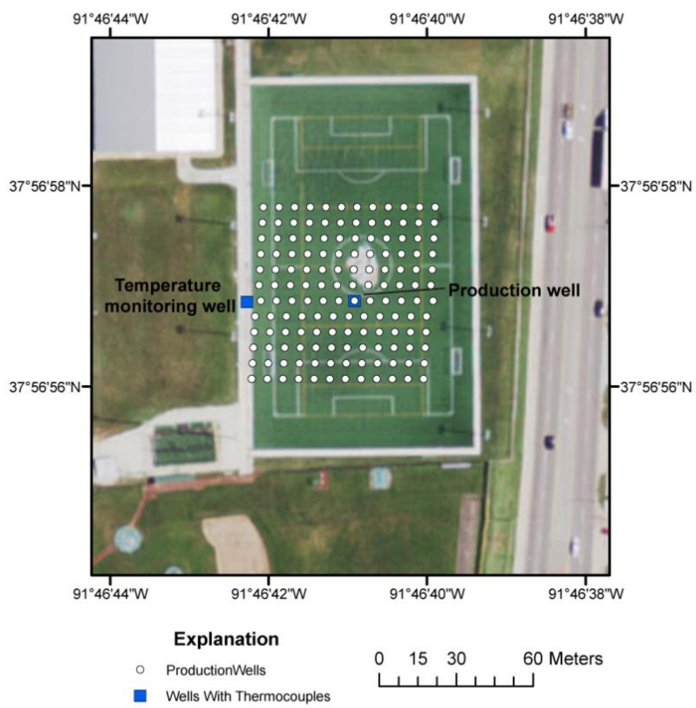

Figure 1.6 Aerial photography of the borehole heat exchanger site.

Figure 1.7 Photograph of thermocouple wire enclosed in concrete electrical box.

Groundwater level data was downloaded from the Missouri Department of Natural Resources Groundwater Monitoring Network Well *USGS 375625091480401 Ramada Inn Rolla* operated in cooperation with the U.S. Geological Survey (USGS, 2016). Water level in the well was recorded using a float (not shown) and encoder as shown in Figure 1.8. The steel tape turns the wheel of the encoder as the float lowers or rises with the water level in the well. Each turn of the encoder wheel is equivalent to a certain change in linear feet of water level. The water level data was used to compare regional saturation of the aquifer to the performance of the BHE. Precipitation was also measured and recorded at the site using a tipping-bucket style rain gage as shown in Figure 1.9.

The flowrate and temperature of the water entering and leaving the BHE for the Gale Bullman Multi-purpose building was provided by The S&T Physical Facilities Department. Well pumping data for the municipal well near the BHE was provided by the city Rolla, Missouri which included pumping time, pumping rate, and water level before pumping.

Figure 1.8 Photograph of the Missouri Department of Natural Resources Groundwater Monitoring Network Well *USGS 375625091480401 Ramada Inn Rolla.*

Figure 1.9 Photograph of the tipping-bucket rain gage at the Missouri Department of Natural Resources Groundwater Monitoring Network Well USGS 375625091480401 Ramada Inn Rolla.

1.4 QUALITY ASSURANCE AND QUALITY CONTROL

A quality assurance check was performed on the Campbell Scientific CR10X (used from August, 2015 through December, 2016) and the Campbell Scientific CR10X (used from January, 2015 through June, 2017) and the Omega SA2C-T thermocouples. The dataloggers where compared to a Fisher Scientific thermometer which was calibrated and tested at the factory. The Fisher Scientific thermometer was positioned with the bulb directly in contact with the thermocouples and secured with electrical tape. The thermometer and thermocouple were placed in a large container of ice water. The temperatures measured by the thermometer and thermocouple were recorded. Warm water was added and allowed to equilibrate. Additional measurements were recorded after each addition of warm water. Both the CR10X and the CR10 with the thermocouple compared favorably to the Fisher Scientific thermometer as shown in Figures 1.10 and 1.11. Both the CR10X and the CR10 measurements had correlation coefficients of 0.99 with the Fisher Scientific thermometer indicating very precise measurements.

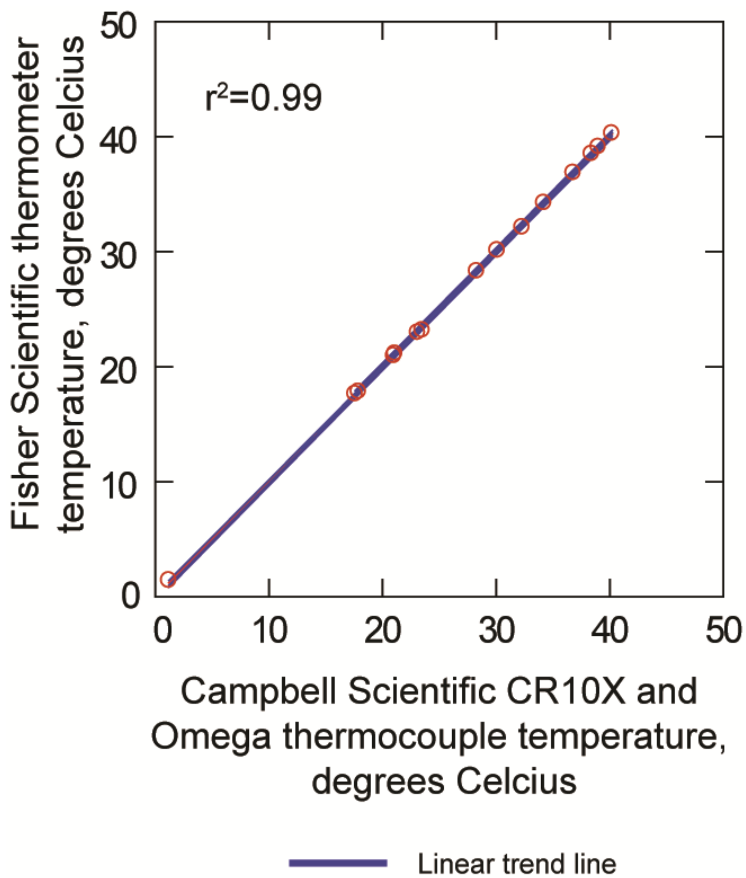

Figure 1.10 Scatterplot comparing the temperatures measured by the Campbell Scientific CR10X and omega Thermocouple and Fisher Scientific thermometer.

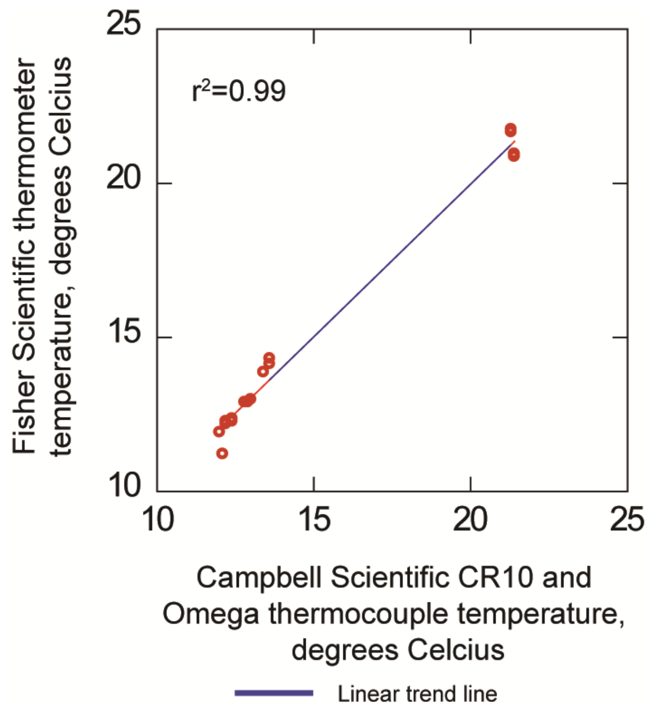

Figure 1.11 Scatterplot comparing the temperatures measured by the Campbell Scientific CR10 datalogger and Omega thermocouple and Fisher Scientific thermometer.

Two thermocouples were installed at the bottom of the production well u-tube both to monitor the temperature but also serve as a long-term quality assurance check. One thermocouple was installed to the incoming water side of the u-tube while the other thermocouple was installed on the outgoing water side of the u-tube. Both thermocouples were separated horizontally by less than 10 centimeters (cm) and less than 10 cm linearly along the u-tube. Temperature of the locations at the two thermocouples generally should remain comparable due to the proximity. The two thermocouples compared favorably as shown in Figure 1.12. The correlation coefficient for the two sets of measurements was 0.92.

The CR10X and CR10 dataloggers both use an onboard thermistor to measure the internal Datalogger temperature. The data logger temperature is used in the calculation of the temperature measured by the thermocouples. Both data logger (two CR10x's or two CR10's) are side by side, confined in a weather proof electrical enclosure which is also confined in a concrete electrical box just below the ground surface. The proximity of the dataloggers and double enclosures should keep both data logger temperatures stable and comparable. Vastly different internal temperatures recorded by the dataloggers could indicate a malfunction of either unit resulting in poor data quality. The internal temperature measurements compared favorably throughout the study as shown in Figures 1.13 and 1.14. Both sets of dataloggers, the CR10X's and the CR10's had correlation coefficients of 0.99 indicating optimum operation.

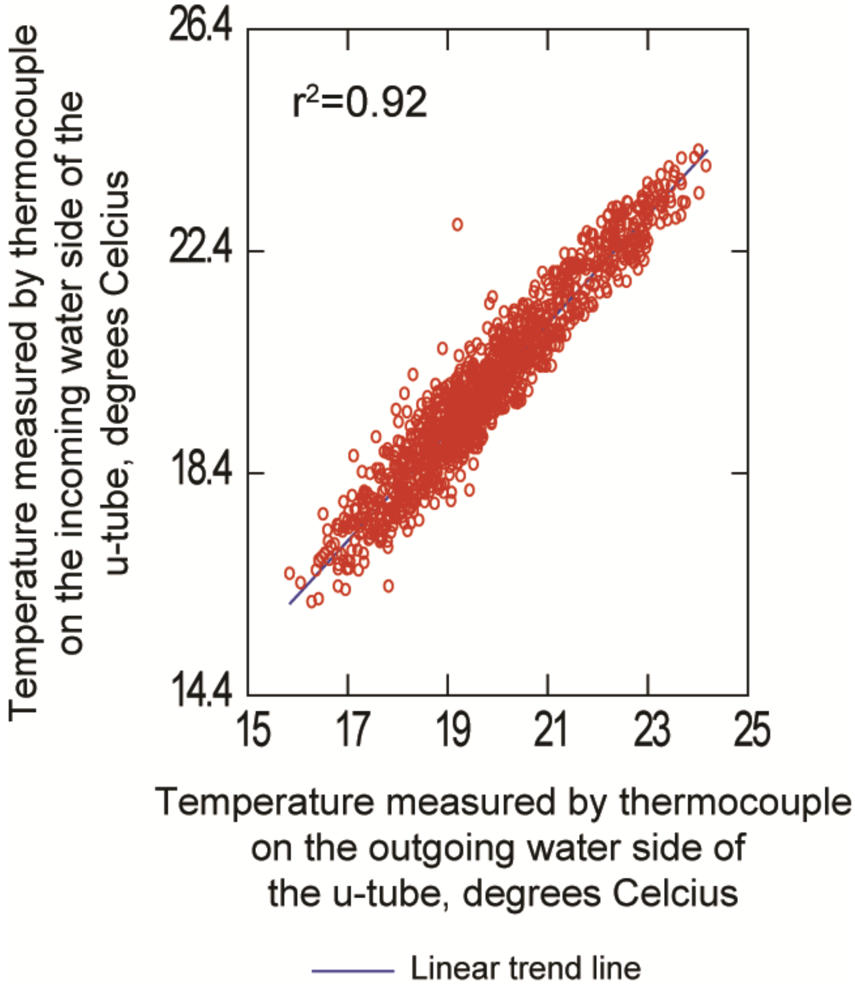

Figure 1.12 Scatterplot comparing the temperature measurements of two collocated thermocouples.

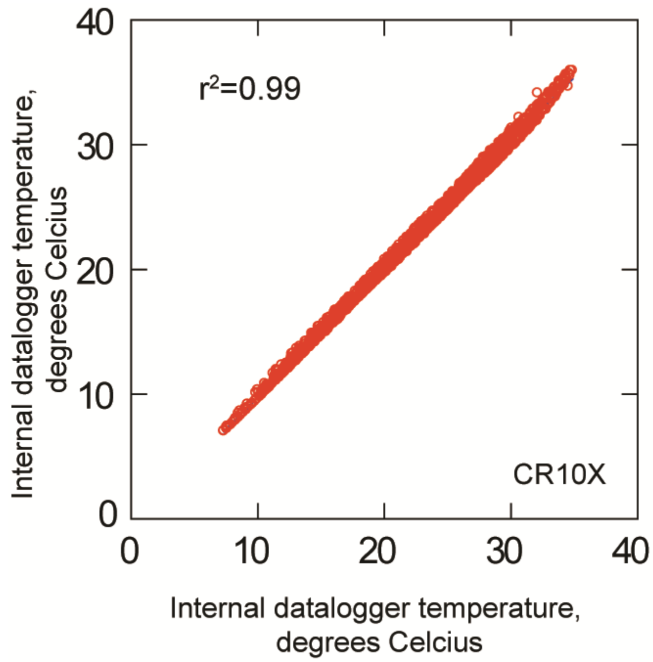

Figure 1.13 Scatterplot comparing the internal temperature measurements of two collocated Campbell Scientific CR10X dataloggers.

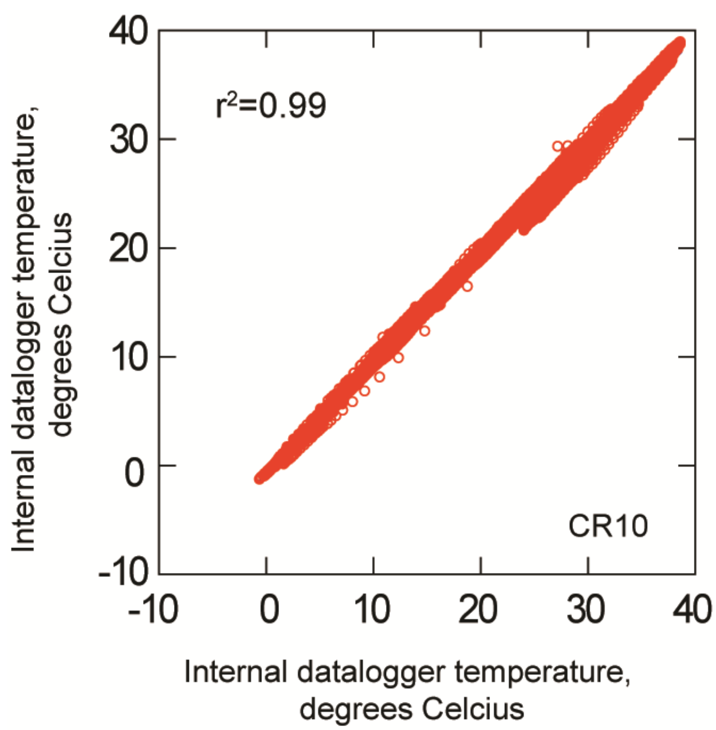

Figure 1.14 Scatterplot comparing the internal temperature measurements of two collocated Campbell Scientific CR10 dataloggers.

The installation of the thermocouples in the production well required extension wire and splices to reach the surface and electrical box for the dataloggers. The deepest thermocouple required 122 m of thermocouple extension wire to reach the surface and 32 m to reach the electrical box on the west side of the BHE. This required up to 154 m of thermocouple extension wire. Additionally, the thermocouple extension wire was spliced near the thermocouple using a western union splice (Ardelean, 1988) that was soldered and covered with heat shrink and electrical tape. The western union splice is much thinner overall compared to traditional thermocouple connectors. Traditional connectors were too large and there was a risk of damage as the u-tube was lowered into the borehole. The splice near the thermocouple was completed in the laboratory before installation. A second splice was made at the surface during the installation so that the extra wire did not interfere with construction. A traditional thermocouple connecter was used to join the extension wire together at the surface.

A test was completed to ensure that the thermocouples operated properly with the addition of the extension wire and splices. A thermocouple was taped to the temperature probe of a Beckman pH meter. The thermocouple readings were made using an Omega handheld thermometer as shown in Figure 1.15. The thermocouple extension wire was spliced near the thermocouple with a western union splice and near the handheld thermometer with a traditional thermocouple connector. Overall, 200 m of thermocouple extension wire was used in the experiment. The extension wire and splices were used to mimic the installation of the thermocouples in the borehole. The thermocouple and temperature probe were place in a large container of near freezing water. The temperature was recorded for both the Beckman pH meter and the thermocouple as the water warmed.

The thermocouple compared favorably to the Beckman pH meter temperature as shown in Figure 1.15. The correlation coefficient was 0.99 indicating that the thermocouple performed accurately and reliably despite the long extension wire and splices.

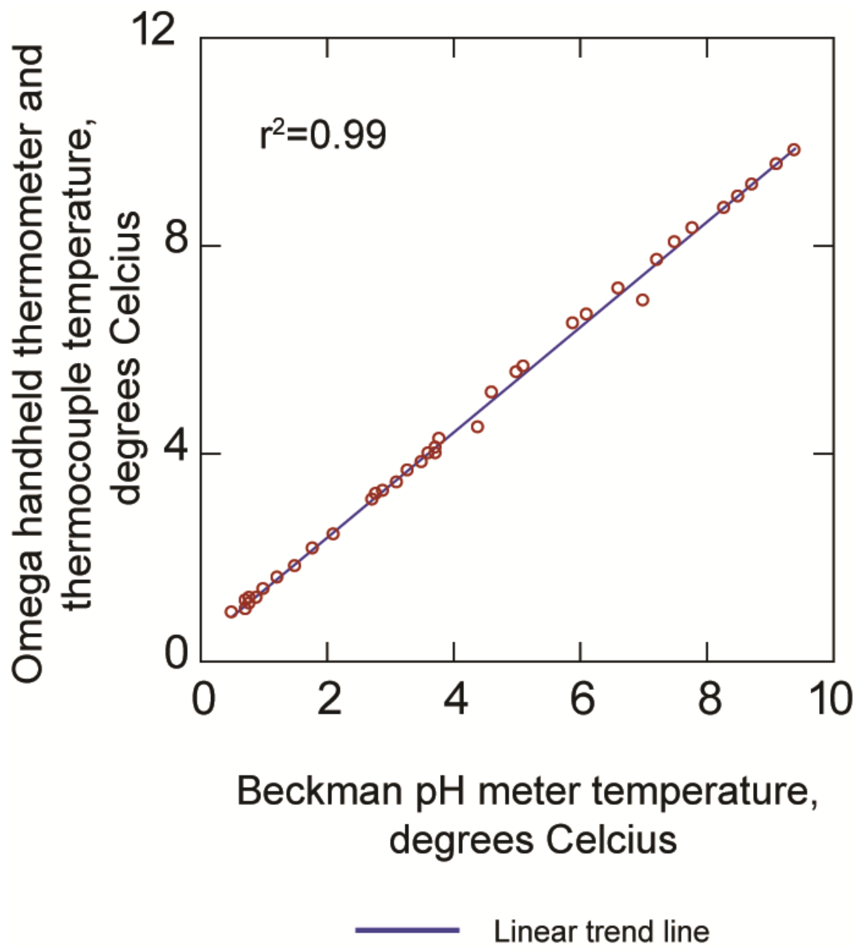

Figure 1.15 Scatterplot comparing the temperature measurements of Omega handheld thermometer and Beckman pH meter temperature probe.

2. GOALS AND OBJECTIVES

The overall goal of this research was to advance the field of large-scale ground coupled heat pump (GCHS) systems by characterizing the effects of changing groundwater conditions and differing lithology on large-scale GCHS systems through long-term observation and analysis of a large-scale GCHP system during operation.

- Objective 1: Evaluate the effects of changes in aquifer saturation on large-scale GCHP systems
    - Hypothesis: Changes in the saturation of the rock and soil surrounding a large-scale GCHP system's borehole heat exchanger (BHE) will have a significant long-term effect on the BHE's performance.
- Objective 2: Evaluate the effects of changes in groundwater flow on large-scale GCHP systems
    - Hypothesis: Changes in the groundwater flow in the rock and soil surrounding a large-scale GCHP system's BHE will have a significant long-term effect on the BHE's performance.
- Objective 3: Evaluate the effects of differing lithology on large-scale GCHP systems
    - Hypothesis: Differing lithology will have significantly different effects on the heat transfer to and from a large-scale GCHP system's BHE.

PAPER

I. THE EFFECT OF SEASONAL GROUNDWATER SATURATION ON THE EFFECTIVENESS OF LARGE SCALE BOREHOLE HEAT EXCHANGERS IN A KARSTIC AQUIFER

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ABSTRACT

A study was completed comparing the effectiveness of the borehole heat exchanger (BHE) of a large scale closed-loop geothermal system to seasonal fluctuations in the saturation of the surrounding rock material. The BHE consisted of 144 production wells drilled to a depth of 122 meters in karstic bedrock. Groundwater levels in a nearby groundwater monitoring well were used to characterize the changes in the saturation of the bedrock. The study showed a significant increase in the effectiveness of the BHE as the saturation of the aquifer increased. The effectiveness of the BHE was typically near 0.8 when saturation was highest. The effectiveness decreased to 0.4 when saturation lowered past a threshold but tended to remain stable as saturation continued to decrease. This study shows strong evidence that single borehole thermal response tests in karstic environments may not reflect the seasonal changes in the saturation of the surrounding bedrock. Proper characterization of the site's subsurface geology, hydrology, and use of multiple borehole thermal response tests during periods of high, low, and median saturation of the surrounding bedrock will better help stakeholders plan and design large scale geothermal systems in karstic environments.

Keywords: Geothermal system; borehole heat exchanger; groundwater; karst; geothermal energy; ground source heat pump

1. INTRODUCTION

The Earth's climate has warmed by 0.6 °Celsius over the past 100 years (Walther et el., 2002) and concern has greatly increased in recent years as new research suggesting human impact on climate change emerges. Research of renewable energy sources, particularly sources that have less emissions of carbon dioxide (CO_2), has hastened in recent years. CO_2 is considered to be one of the major contributors to climate change. Ground-coupled heat pump (GCHP) systems, also referred to as geothermal, are beginning to play a more prominent role in decreasing the amount of CO_2 released into the atmosphere. These systems reject or extract heat from the subsurface using a borehole heat exchanger (BHE). The usage of these systems has increased 10 percent annually in about 30 countries from 1994 to 2004. Most of the growth has occurred in the United States and Europe, although other countries such as Japan and Turkey have also been increasing in capacity for these systems (Lund et al., 2004). The effects of seasonal and diurnal temperature changes are diminished with depth, and ground temperature measurements have shown that they are relatively stable below a certain depth (Florides et al., 2011) due to the high thermal inertia of soil and rock (Florides and Kalogirou, 2007).

Florides et el. (2011) drilled single boreholes at eight sites on the island of Cyprus to characterize the thermal properties of the subsurface. The sites were chosen in different areas in order to characterize seaside, inland, semi-mountainous, and mountainous regions of the island so the data would be available for further geothermal development on the island. The lithology in the different areas included sandy marls, chalk, limestone and sandstone. U-tubes were installed in the boreholes with Omega k-type thermocouples attached to the u-tubes at multiple depths. Florides et el. (2011) conducted thermal response tests (TRT) on the wells using the Kelvin line source model and characterized the thermal gradient of the subsurface at each site. The TRT is done by maintaining a constant heat in the circulation water of the u-tube and recording the inlet and outlet temperature of the u-tube and the flowrate (Ingersoll et al., 1954; Carslaw and Jeager, 1959; Mogensen, 1983). TRTs are used to determine the thermal conductivity of the geologic material surrounding a single well BHE. The study showed that ground temperatures at the eight sites began to remain stable at about 7 to 8 meters (m) below land surface.

Piscaglia et el., (2016) presented a case study of a large-scale GCHP system operating in Urbino in Central Italy. The system was used for the heating and cooling of a 1,152 square meter (m^2) 2 story commercial building. The BHE consisted of 6 production wells drilled into marly-limestone reservoir rock to a depth of 100 m. A temperature monitoring well was drilled 2.2 m from one of the production wells and instrumented with 11 resistance temperature detectors (RTD) from the surface to the maximum depth of 100 m. Urbino is in a heating-dominated climate which resulted an unbalanced heat extraction and rejection into the reservoir rock. This resulted in a decrease in the overall temperature of the reservoir rock from May of 2012 to September of 2014. Piscaglia et el., (2016) also showed that snow melt indirectly affected the temperature of the reservoir rock by infiltrating the ground which highlights the important role of groundwater in GCHP.

Groundwater conditions can greatly affect the effectiveness of GCHPs and the associated BHEs by changing the thermal properties of the surrounding rock (Clauser, and Huenges, 1995; Robertson, 1988, Albert et al., 2016). Mohamed et al. (2015) showed that fluctuations in the groundwater level produced noticeable results in the heat recovery of the bench scale model GCHP. High groundwater levels enhanced the heat recovery in poorly graded sand in their bench scale model of a GCHP. Due to the effects of groundwater on the performance of these systems, Molina-Giraldo et al., 2011, Diao et al., 2004, and Fan et al., 2007 have incorporated groundwater advection into GCHP models. Chiasson et el., (2000) used numerical modeling to show that groundwater flow significantly enhances heat transfer in sands, gravels, and fractured rocks with high hydraulic conductivity. Many rock formations such as sandstone, and karstic dolostone and limestone, have both primary intergranular and secondary fracture permeability and the degree of saturation of these types of rock can greatly influence the thermal properties (Busby et al., 2009). Little is known about the effects of changes in the saturation of the aquifer on large GCHP systems and how the amount of energy rejected or extracted from the subsurface changes.

The use of GCHP systems for institutional climate control is beginning to be adopted in the United States. For example, Ball State University's (BSU) GCHP system went online in the spring of 2012 and is currently considered the largest in the nation. This system consisted of 3,600 boreholes drilled to depths of 122 to 152 m deep. While BSU's website does not report the lithological setting of the BHE, Indiana Department of Natural Resources (IDNR) well number 421719 was completed on December 23, 2009 on the campus of BSU (IDNR, 2009). It was drilled to a depth of 122 m through 7 m of clay, 2 m of gravel, a second 9-m layer of clay, 43 m of limestone, and 61 m of shale (IDNR, 2009). The GCHP system heats and cools 47 buildings (511,000 m^2) on the 295 hectare campus which helped reduce CO_2 emissions by 77,000 metric tons annually by taking its fossil-fuel boilers offline (BSU, 2016).

The Missouri University of Science and Technology (S&T) completed a similar scale GCHP system in 2014 in an effort to reduce heating and cooling costs and water use. This paper describes the impact of seasonally variable water levels, or percent saturation, on the BHE system performance at one of the S&T GCHP subsystems. The BHE was installed in nearly 122 m of karstic dolomite and sandstone. A temperature monitoring well was installed adjacent to subject subsystem well fields and instrumented with thermocouples to monitor the overall temperature of the subsurface near the system. Similar instrumentation was installed in a production BHE well near the center of the

BHE well field but was not referred to in this particular study. The effectiveness of the BHE was calculated using the temperature of the subsurface near the geothermal system, flowrate, and temperature of the water in the closed-loop BHE as it entered the aquifer and as it left the aquifer. This effectiveness was compared to local aquifer saturation estimated from water levels in a nearby groundwater observation well.

When the S&T GCHP system was completed in 2014, it was one of the largest systems in the country with 789 boreholes extending through 122 to 134 m of karstic bedrock. The multiple BHEs serve three primary campus GCHP system plants. The BHE in this study serves a satellite plant at the Gale Bullman Multi-purpose Building which is 42,178 m^2 and houses two gymnasiums, pool, racquetball courts, fitness center, and multiple offices. The geothermal plants on the S&T campus consist of 500 tons of heat recovery chillers for heating and cooling, supplementary cooling towers, and gas-fired boilers. The cooling towers and boilers are generally used during extreme hot and cold periods for cooling or heating. Overall, the new system has met great success. Energy is now stored in the subsurface which reduces the need for evaporative cooling towers. This, along with a replacement of older leaky pipes, has reduced the campus water use by 85 million liters per year. The overall system replaced an aging 70 year old coal- and woodchip-fueled boiler power plant which has reduced annual energy consumption by 57 percent. It has also helped S&T reduce its overall carbon footprint by reducing CO_2 emissions by 23,000 metric tons per year (S&T, 2016).

2. METHODS

2.1 SITE DESCRIPTION

S&T is located in Rolla, Missouri in an area where the principal bedrock aquifer consists of Ordovician dolostones and sandstones that are subject to the widening of fractures by solution and is therefore classified as karstic (Jennings, 1971). The formations underlying the site are predominantly dolostone and to a lesser extent, sandstone (Vandike, 1992). The BHE used in this study is part of the Gale Bullman Multi-purpose Building satellite system. The Bullman BHE well field consists of the 144 wells shown on Figure 1, each well being drilled to a depth of 123 m below land surface.

The wells' completion interval typically consisted of residuum (6 m thick) and 3 karstic formations which are the Jefferson City Formation (46 m; dolostone), the Rubidoux Formation (37 m; dolostone and sandstone), and the Gasconade Formation (34 m; dolostone and cherty dolostone). All of these formations are good producers of water and are part of the Ozark Aquifer which is a major source of water for parts of Missouri, Kansas, Oklahoma, and Arkansas (Imes and Emmet, 1994, Miller and Vandike, 1997; Vandike, 1992).

A 3.2-centimeter (cm) diameter Geoguard high-density polyethylene (HDPE) u-tube, manufactured by Dura-line™, was installed in each of the 15.2-cm diameter borings for the 144 closed loop geothermal wells. The u-tubes were then grouted in using a mixture of graphite, quartz sand, and GeoPro's™ Thermal Grout Lite, which is specifically designed to maximize the performance of BHEs.

The circulation flood for the BHE system generally has a flowrate ranging from 0.97 cubic meters per minute (cpm) to 1.14 cpm during mild outside weather conditions but can increase to as high as 2.49 cpm during hot or cold weather conditions. The initial TRT for this well field was conducted from June 26, 2011 to June 28, 2011 in order to determine the thermal properties of the surrounding rock.

2.2 INSTRUMENTATION

The temperature monitoring well was centrally located 6 m from the center of the west side of the BHE well field as shown in Figure 1. Eight Omega™ SA2C-T thermocouples were installed at 15 m intervals on a 122 m length of 3.8-cm diameter HDPE pipe that extended from the ground surface to the bottom of the 122 m borehole well shown in Figure 1. Florides et el., (2011) installed Omega k-type thermocouples attached to the u-tubes at multiple depths. The SA2C-T are self-adhesive t-type thermocouples specifically designed for curved surfaces such as pipes. T-type 16-gauge extension wire was used to reduce the resistance used in the relatively long distances from the bottom of the well to the surface. The thermocouple wire extended from the thermocouples to an electrical box installed on the west side of the well field. Two Campbell Scientific CR10 model data loggers were used to record the thermocouple

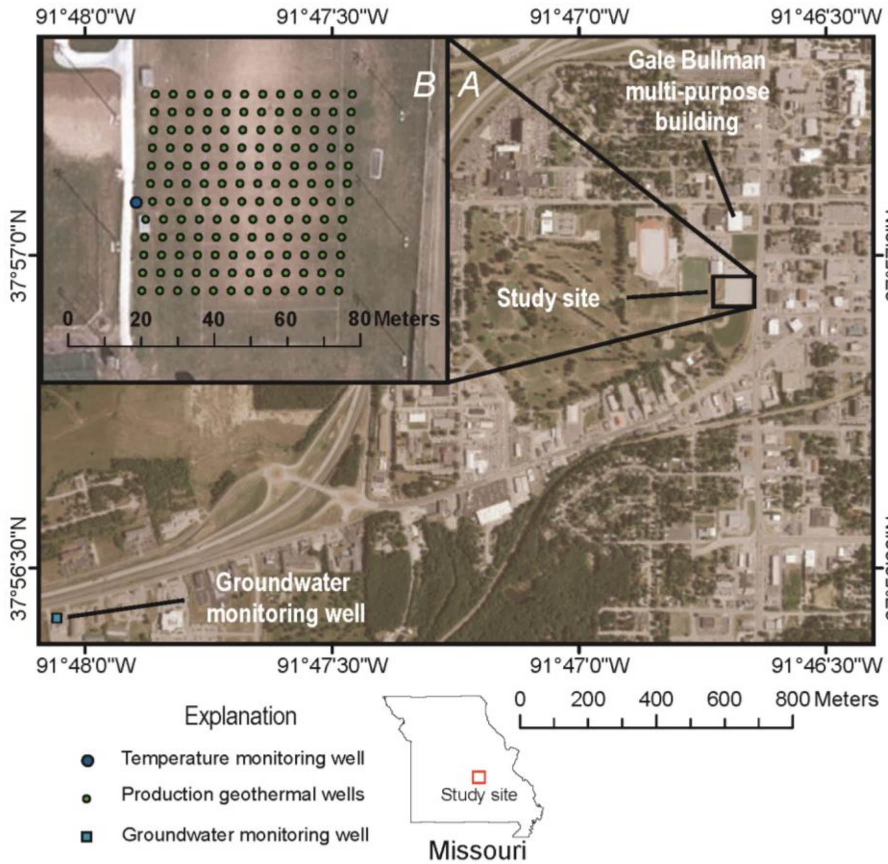

Figure 1. Location of study site in Rolla, Missouri, 2015-16 (A) and plan view of the borehole heat exchanger (B).

readings. Temperature data was recorded at 60 minute (min) intervals from September 2015 through December 2015 and 30 min intervals from January 2016 through July 2016.Temperature was recorded at the following depths: 15 m, 30 m, 46 m, 61 m, 76 m, 91 m, 107 m, and 122 m below land surface. The temperature of the circulation water in the geothermal system was recorded by the HVAC system before it was pumped into the subsurface and as it re-entered the building after leaving the subsurface, and the pumping rate was recorded at 15 minute intervals.

Water level data was collected from the Missouri Groundwater Observation Network well located 1.3 miles from the BHE well field as shown on Figure 1 which was owned and operated by the Missouri Department of Natural Resources and operated in cooperation with the U.S. Geological Survey (USGS, 2016). Water levels were recorded every 30 minutes using a vented submerged pressure transducer. The overall saturation of the aquifer at the BHE was estimated by dividing the reported water level by the maximum depth of the BHE (122 m) and multiplying by 100. Precipitation was also recorded at the Missouri Groundwater Observation Network well. Total precipitation for each 30 minute interval was measured using a tipping bucket rain gage.

2.3 DATA ANALYSIS

The effectiveness of a BHE is expressed as the ratio of the heat transfer rate to the maximum theoretical heat transfer rate as shown in Equation 1 (Incropera and Dewitt, 2002).

$$\varepsilon = \frac{h}{h_m} \tag{1}$$

The energy gained or rejected from the ground loop (h) was calculated in Equation 2 (Incropera and Dewitt, 2002) where T_i is the temperature of the water entering the BHE, To is the temperature of the water leaving the BHE, C_p is the specific heat capacity of water, ρ_w is the density of water, and the flow rate of the water in the ground loop is q.

$$h = (T_i - T_o)C_p\rho_w q \tag{2}$$

The maximum theoretical heat transfer rate from the ground loop (h_m) was calculated in Equation 3 (Incropera and Dewitt, 2002) where Ta is the mean temperature of the aquifer as measured by the 8 thermocouples from 15 m to122 m below ground surface at the temperature monitoring well. A specific heat capacity of 4.18 joules per gram change in temperature Celsius and density of 1,000 kilograms per cubic meter were used for Equations 2 and 3.

$$h_m = (T_i - T_a)C_p\rho_w q \tag{3}$$

Changes in effectiveness of the BHE can be explained by a single borehole's performance as predicted by the Kelvin's line source model where T(r) is temperature in subsurface at any distance from the line source, r is distance from the line source, T_0 is the uniform initial rock temperature, h is the heat transfer rate of the line source, k_s is the rock thermal conductivity, α_s is the rock thermal diffusivity, t is the time since the start of operation, β is the integration variables as shown in Equation 4. This equation can be used to calculate a time in which the temperature at some radius from a line source of constant heat reaches equilibrium with the temperature from the line source. The line source, in this case, would be the nearest production well, and the radius in this case would be the location of the temperature monitoring well. Because of its simplicity, Kelvin's line source model is generally used to evaluate thermal response test data from wells (Mogensen, 1983; Eskilson, 1987; Hellström, 1991).

$$T(r) - T_0 = \frac{q}{2\pi k_s}\int_x^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta = \frac{\mathrm{h}}{2\pi k_s}l(x)$$

$$x = \frac{r}{2\sqrt{\alpha_s t}} \qquad (4)$$

The length of time for the temperature of the surrounding aquifer as measured in the temperature monitoring well to increase or decrease to equal that of the temperature of the water in the BHE can be calculated using the thermal diffusivity and thermal conductivity of the rock material and by applying them to the Kelvin Line Source Theory.

The changes in effectiveness of the BHE in relation to changes in saturation of the aquifer were compared by calculating and comparing the median effectiveness values with associated saturation from the intervals 55.0–53.8, 53.8–52.5, 52.5–51.3, 51.3–50.0, 50.0–48.8, 48.8–47.5, 47.5–46.3, and 46.3–45.0 percent. The overall efficiencies with the saturation intervals were also compared by plotting boxplots of the efficiencies of each group of associated saturation values. This provided insight into ranges of efficiencies and how they changed as saturation changed.

The Shapiro-Wilks Test (Shapiro and Wilk, 1965) was used to determine if the population of effectiveness values was normally distributed. The calculated p-value for the Shapiro-Wilk Test was 0.0 indicating the null hypothesis can be rejected with a very low probability of falsely rejecting the null hypothesis as shown in Table 1.

The Wilcoxon–Mann–Whitney Test (Mann and Whitney, 1947; Wilcoxon, 1945) was used to evaluate if the BHE effectiveness changed according to the degree of saturation. Table 1 presents the results of the Wilcoxon-Mann-Whitney testing. Only effectiveness values in which the GCHP system did not reverse from heating or cooling within the past 6 hours were used. Frequent reversals and very small differences in the inlet and outlet temperature of the BHE are typical during mild weather.

Table 1. The statistical tests used in this study, the chosen significance, and explanation of the results.

Statistical Test	p-value	Hypothesis
Shapiro-Wilk Test	>0.05	The data are normally distributed
	<0.05	The data are not normally distributed
Wilcoxon–Mann–Whitney Test	>0.05	The two groups are equal
	<0.05	One group is larger than the other

3. RESULTS AND DISCUSSION

The estimated aquifer saturation ranged from approximately 55.0 to 45.0 percent during the study. The lower quartile was 50.6 percent and the upper quartile was 52.7 percent. The median saturation was 51.8 percent and most of the estimated saturation levels fall in the 52.5–51.3 percent interval (2,195 cases). The 55.0–53.8 percent interval (72 cases), 47.5–46.3 percent interval (71 cases), and the 46.3–45.0 percent interval (29 cases) had the fewest cases as water levels in these ranges were less frequent as listed in Table 2.

Table 2 shows that the median effectiveness of the BHE tends to decrease with decreasing saturation of the aquifer but becomes asymptotic at effectiveness near 0.40 at the 51.3–50.0 percent saturation interval as shown in Table 2.

Table 2. Median effectiveness of the borehole heat exchanger excluding all values that the system reversed from either heating or cooling within the past 6 hours.

Percent saturation of the aquifer	All cases without a 6 hour heating/cooling reversal	
	Cases	**Median effectiveness**
55.0–53.8	72	0.88
53.8–52.5	1,922	0.73
52.5–51.3	2,195	0.43
51.3–50.0	1,536	0.40
50.0–48.8	935	0.40
48.8–47.5	431	0.40
47.5–46.3	71	0.41
46.3–45.0	29	0.38
Total	7,191	

The circulation fluid flow rate within the u-tube also has a noticeable relationship to effectiveness as shown in Figure 2. The effectiveness of the BHE tends to decrease as flowrate of the water within the BHE increases. This is explained by the length of time the water remains in the heat exchanger before returning the building. The temperature of the water of the BHE has less time to equilibrate to the temperature in the surrounding aquifer when flow rate increases; likewise, temperature of the water has more time to equilibrate as the flow rate decreases.

Two distinct population groups separated by an effectiveness value of 0.5 are visible in the Figure 2. Figure 2A shows the relation of flow rate and effectiveness for all percent saturation values greater than 52.5 percent. Ninety-four percent of the population (n=642) falls in the higher effectiveness group while the remainder (n=42) of the population have effectiveness values below 0.5. This results in a ratio of the population of the higher effectiveness group to the population of the lower effectiveness group of 15.3. The ratio of the population of the higher effectiveness group to the population of the lower effectiveness group decreases as saturation decreases from Figure 2A (15.3) to Figure 23D (0). There is only a small population of 85 that occupies the lower

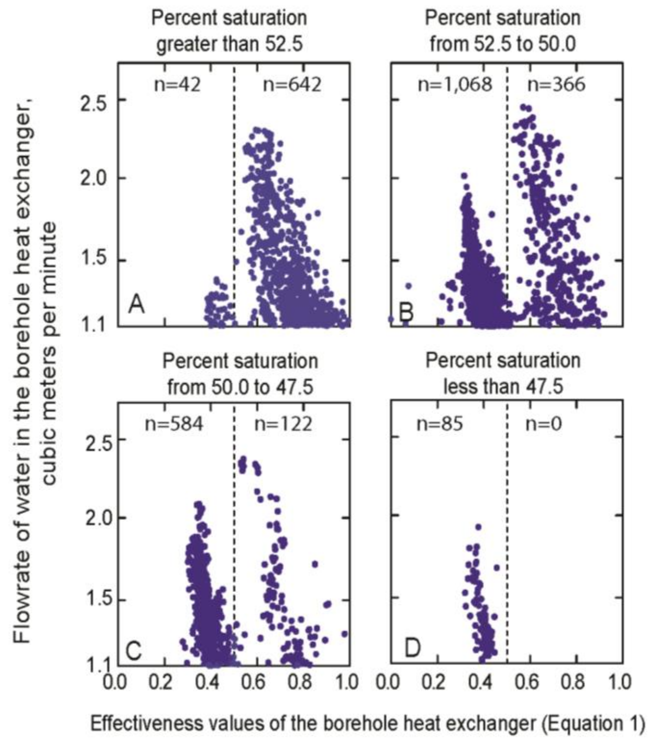

Figure 2. Comparison of all effectiveness values from 0 to 1 and flow rates greater than 1.1 cubic meters per minute for the borehole heat exchanger and grouped by water level. Dashed line indicates effectiveness of 0.5 (n is the number of values that are less than [left] or greater than [right] an effectiveness of 0.5).

effectiveness curve in Figure 2D when the saturation lowers beyond 47.5 percent. This also shows a decrease in effectiveness of the BHE as saturation decreases but also shows a very sharp distinction between the higher and lower effectiveness values. The BHE effectiveness tends to be less than 0.5 when saturation of the aquifer is less than 52.5 percent and effectiveness tends to be greater than 0.5 when saturation of the aquifer is greater than 52.5 percent. While there is a noticeable contrast between the two populations, there is generally no noticeable intermediate effectiveness near 0.5. The data shows that the effectiveness of the BHE ranged from greater than 0.5 or less than 0.5 during periods of high and low saturation despite a trend of decreasing effectiveness with decreasing saturation. This is likely explained by the pumping of nearby municipal wells that cause the estimated saturation of the aquifer from the water levels in the groundwater observation well and the actual saturation of the aquifer at the BHE to vary.

The Wilcoxon–Mann–Whitney test was used to determine if there was a significant difference between the efficiencies grouped by percent saturation of the aquifer as shown in Table 2. Test 1, 2, and 3 compare the 3 groups with the three highest percent saturation intervals. Group A (55.0–53.8 percent saturation) has a median effectiveness of 0.88 while group B (53.8–52.5 percent saturation) has a lower median effectiveness of 0.73 in Test 1. The resulting p-value in test 1 was 0.00 indicating that the Group A (higher saturation) effectiveness values are statistically larger than the Group B (lower saturation) effectiveness values.

Test 2 also resulted in a p-value of 0.00 as shown in Table 2. Group A (53.8–52.5 percent saturation) had the higher median effectiveness of 0.73 and group B (52.5–51.3 percent saturation) had the lower median effectiveness of 0.43 indicating that group A, with the higher percent saturation, was statistically larger. Test 3 also resulted in a p-value of 0.00 as shown in Table 2. Group A (52.5–51.3 percent saturation) had the higher median effectiveness of 0.43, and group B (51.3–50.0 percent saturation) had the lower median effectiveness of 0.40 (table 21), indicating that group A, with the higher percent saturation, was statistically larger.

Tests 4, 5, and 6 show a distinct change in the trend of the differing effectiveness for the groups. The results of the Wilcoxon–Mann–Whitney test reported p-values of 0.67 (test 4), 0.36 (test 5), and 1.00 (test 6) as shown in Table 2. The groups with percent saturation from 53.3 to 46.3 are not statistically different.

Test 7 indicates that effectiveness may begin to decrease once again as percent saturation continues to decrease. Test 7 resulted in a p-value of 0.02 as shown in Table 2. Group A (47.5–46.3 percent saturation) had the higher median effectiveness of 0.41 and group B (46.3–45.0 percent saturation) had the lower median effectiveness of 0.38 (Table 2) indicating that the group of efficiencies with the higher percent saturation is statistically larger. However, these two groups also have the smallest population size, 71 for the group with a percent saturation from 47.5 to 46.3 and 29 for the group with a percent saturation from 46.3 to 45.0.

Test 8 compared the effectiveness of the group with corresponding percent saturation greater than 51.3 percent with the group with corresponding saturation less than 51.3 percent due to the difference in effectiveness of the two groups. The effectiveness values with a corresponding saturation less than 51.3 percent were the largest ranging from 0.88 (55.0–53.8 percent saturation) to 0.43 (52.5–51.3 percent saturation). The median effectiveness values with a corresponding saturation less than 51.3 percent were the smallest ranging from 0.41 (47.5–46.3 percent saturation) to 0.38 (46.3–45.0 percent saturation). The p-value for test 8 was 0.00 which indicates that the efficiencies from group A, with corresponding saturation greater than 51.3 percent, was statistically larger than group B, with corresponding saturation less than 51.3 percent.

Precipitation may indirectly affect the effectiveness of the BHE through the enhancement of heat recovery and rejection by increasing the saturation of the aquifer or perhaps by infiltration through the aquifer. The largest amount of rain fall during the study was in November (27.4 cm) and December (27.8 cm) of 2015. The effectiveness in November 2015 and the following four months ranged from 0.66 to 0.82 which was the highest range during the study. Saturation of the aquifer from December 2015 to April 2016 was also the highest during the study ranging from 52.0 to 52.8 percent as shown in Table 4.

Table 3. The results of the Wilcoxon–Mann–Whitney test comparing consecutive groups of efficiencies grouped by corresponding water levels. The shaded p-values indicate that the Group A effectivness values (higher percent saturation; Table 1) are statistically larger than the correspond Group B effectivness values (lower percent saturation; Table 1).

	Saturation range			
Test	**Group A**	**Group B**	**P-value**	**Explanation**
1	55.0–53.8	53.8–52.5	0.00	Group A is statistically higher
2	53.8–52.5	52.5–51.3	0.00	Group A is statistically higher
3	52.5–51.3	51.3–50.0	0.00	Group A is statistically higher
4	51.3–50.0	50.0–48.8	0.67	No difference in the groups
5	50.0–48.8	48.8–47.5	0.36	No difference in the groups
6	48.8–47.5	47.5–46.3	1.00	No difference in the groups
7	47.5–46.3	46.3–45.0	0.02	Group A is statistically higher
8	> 51.3	< 51.3	0.00	Group A is statistically higher

Table 4. Monthly summary statistics for the borehole heat exchanger effectiveness, saturation of the aquifer, and precipitation.

Month	Median effectiveness	Cases	Mean saturation	Cases	Total precipitation (cm)	Cases
Aug-15	0.43	358	50.8	838	4.4	838
Sep-15	0.44	491	50.6	1,212	1.8	1,439
Oct-15	0.52	224	50.5	1,488	4.3	1,488
Nov-15	0.76	120	51.4	1,440	27.4	1,440
Dec-15	0.66	239	52.1	1,485	27.8	1,485
Jan-16	0.66	286	52.3	1,488	2.2	1,488
Feb-16	0.77	749	52.0	1,392	3.6	1,392
Mar-16	0.82	831	52.3	1,486	6.5	1,486
Apr-16	0.52	685	52.8	1,440	8.1	1,440
May-16	0.45	882	51.4	1,488	11.8	1,488
Jun-16	0.39	1402	50.3	1,440	4.1	1,440
Jul-16	0.38	1038	50.7	1,169	16.1	1,169

The total energy transferred to or from the BHE during this study was estimated to be 6.7 terajoules (TJ). A threshold percent saturation of 51.3 was chosen based on the median effectiveness for the saturation ranges shown in Table 2 and the results of the Wilcoxon-Mann-Whitney Test shown in Table 3. An effectiveness of 0.40 was chosen as representative for absolute total energy transferred with corresponding percent saturation less than 51.3 percent, and an effectiveness of 0.75 was chosen as representative for absolute total energy transferred with corresponding percent saturation greater than 51.3 percent based on the results found in Table 2. The total potential energy transferred from or to the BHE that was possible during this study was estimated to be 9.2 TJ if the aquifer saturated greater than 51.3 percent for the whole period. An energy loss of 2.4 TJ was estimated during periods in which the overall saturation of aquifer was less than 53.1 percent. The total annual energy transferred to or from the BHE could increase by as much as 37 percent if the saturation of the aquifer remained greater than 51.3 percent throughout the year. This indicates that changes in the saturation of the surrounding bedrock have a large influence on the effectiveness of a large scale GCHP and BHE. Further details of the method used for this calculation is located in section 2.3.

In some cases, the calculated effectiveness was greater than the theoretical limits of 1 or less than 0. This dissipation of heat from the u-tube to the surrounding subsurface environment is not instantaneous and depends on the saturation of the rock. During months with mild temperatures, the geothermal system can often switch from rejecting energy into the surrounding rock to extracting energy from the surrounding rock over a relatively short time period. These quick reversals may suggest that the mean measured temperature near the well field may not accurately reflect the temperature of the aquifer in proximity to the individual production wells and may be a source of error during mild temperatures. This can be amplified when there are very small differences in the temperature of the water entering the ground loop (T_i) and the mean temperature of the aquifer (T_a) which can result in effectiveness values greater than 1 or less than 0. This tends to happen during periods of mild weather such as April and October, resulting in a near zero net energy exchange of the BHE with the surrounding rock as shown on Figure 3. These months also have the most system reversals from heating or cooling as shown in Figure 3. Therefore, only efficiencies in which the system did not reverse within 6 hours were used to calculate the median efficiencies and compare groups used in the Wilcoxon-Mann-Whitney test to reduce error. However, all data was used to calculate the total energy exchange and the predicted total energy exchange between the borehole heat exchanger and the surrounding rock.

Figure 4 shows that the water levels in the ground water observation well used in this study have declined steadily since data collection started in 1978. The rate of the mean water level decline began in 2000, but the short term variability has significantly increased over the measurement period. The lowest recorded water level (65.22 m below land surface) was recorded in June of 2016, and that level is equivalent to the lowest estimated saturation range used in this study (46.3–45.0 percent). The trend for water levels at this site may continue to decrease due increased water use. This may cause long-term effectiveness of the BHE to decrease. Thus, there may be the future need for supplemental heating and cooling systems at the Bullman building, especially during periods of extreme heat, cold, and drought. The initial TRT for this well field was conducted from June 26, 2011 to June 28, 2011 in order to determine the thermal

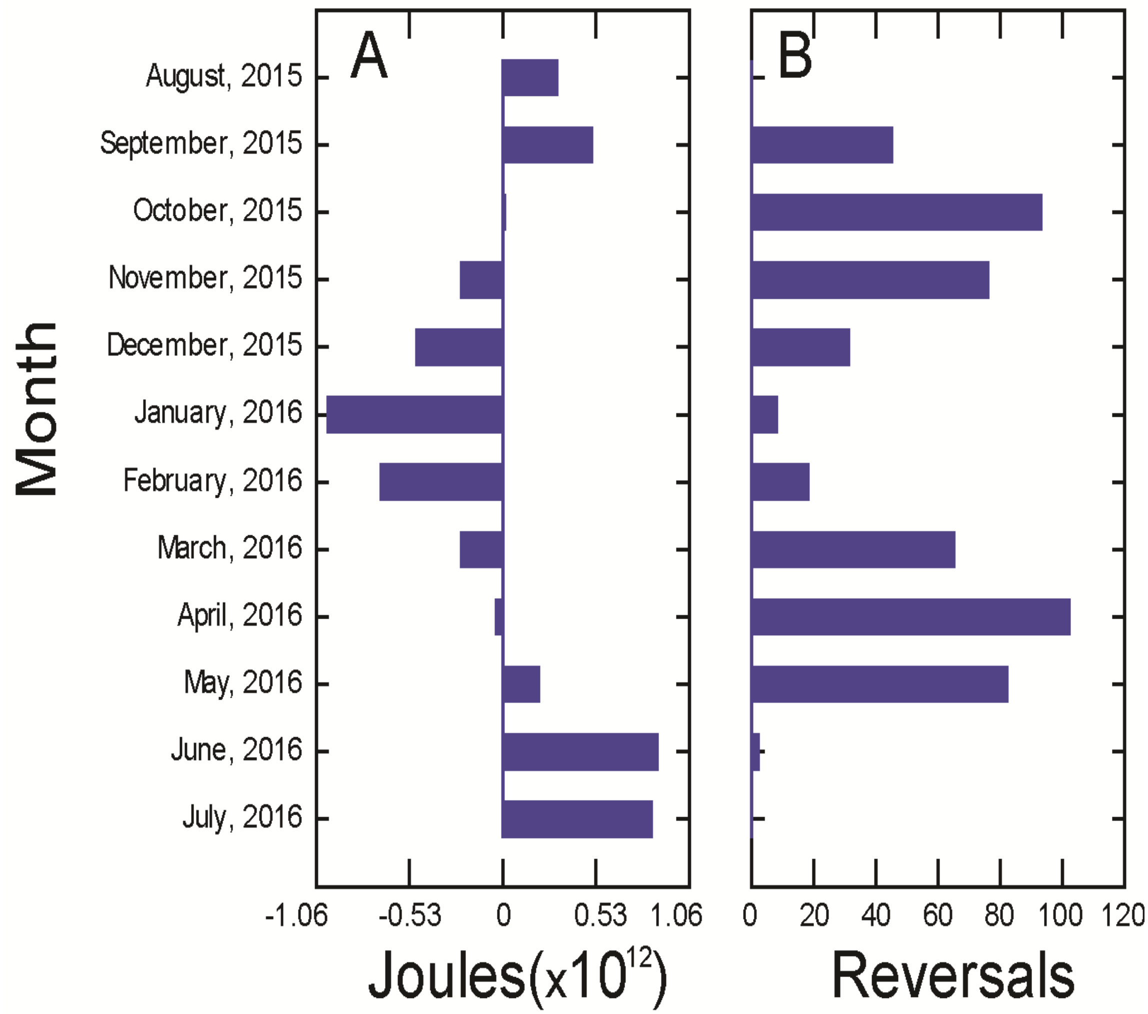

Figure 3. Comparison of the net amount of energy exchange between the borehole heat exchanger and the aquifer (A) and the number of times the system reversed from heating to cooling or cooling to heating (B).

properties of the surrounding rock. Water levels in the well during the test were higher relative to the water levels measured subsequently during the operation of the BHE system and presented in the results section. The saturation of the aquifer during the TRT remained near 54 percent throughout the test with the exception of the last few hours of the test where the saturation fell to 53 percent which corresponds to the highest associated BHE effectiveness shown in Table 1.

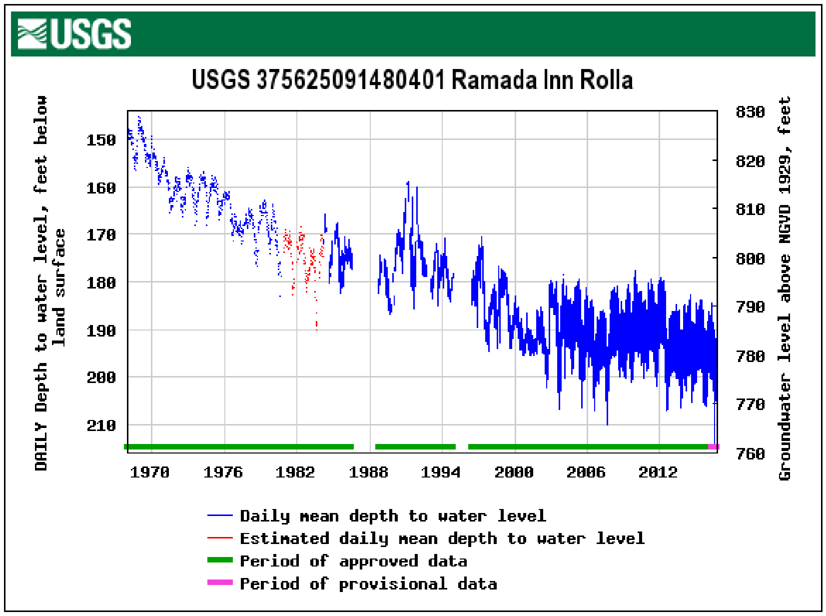

Figure 4. Daily mean water levels in the Missouri Department of Natural Resources Ramada Inn groundwater observation well (Figure 1) from 1968 to 2016 (USGS, 2016).

4. CONCLUSIONS

The data in this study shows that aquifer saturation reflected by ground water levels near the BHE affect the overall effectiveness of an institutional GCHP system in a karstic aquifer. BHE effectiveness tends to increase as a function of the degree of saturation in the aquifer which was reflected by water level in this study. The decrease in effectiveness is asymptotic which may reflect rapid variations in secondary porosity such as fractures which are common in karstic aquifers and more gradual variations in the primary porosity within the grains. Precipitation has an indirect influence on the effectiveness of the BHE. Months following periods with large amounts of precipitation tended to have higher BHE effectiveness. Stakeholders in these large GCHP systems should review historical water level records to account for future water level changes in these karst systems. This study has shown that a TRT should be conducted multiple times when water levels are more reflective of median and upper and lower ranges of saturation. Additional TRTs could be incorporated to the feasibility study in the early stages of a large geothermal project and will yield results that will be more in line with the seasonal changes within the aquifer.

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II. THE OBSERVED EFFECTS OF CHANGES IN GROUNDWATER FLOW ON A BOREHOLE HEAT EXCHANGER OF A LARGE SCALE GROUND COUPLED HEAT PUMP SYSTEM

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ABSTRACT

A study was completed comparing the effectiveness of the borehole heat exchanger (BHE) of a large scale closed-loop geothermal system to changes in groundwater flow as a result of the periodic pumping of a large municipal well. The BHE consists of 144 production wells drilled to a depth of 122 meters (m) in karstic bedrock of the Ozark Aquifer. Estimated groundwater flows ranging from 15 to 1.1×10^{-3} m per year were observed and effectiveness of the BHE during these periods was calculated to understand the effects of groundwater flow on the system. The changes in the effectiveness of the BHE during periods of high and low groundwater water flow were compared to a previous study's estimates of the changes in the effectiveness of the BHE due to changes in aquifer saturation. Overall, the changes in the saturation of the aquifer tended to have the greatest effect on the effectiveness of the BHE.

Keywords: Geothermal system; borehole heat exchanger; groundwater; groundwater flow; geothermal energy; ground source heat pump.

1. INTRODUCTION

The rising cost of fossil fuels and increasing concern for the release of greenhouse gases from the use of fossil fuels has accelerated research into renewable energy sources. Ground-coupled heat pump (GCHP) systems have been shown to be effective for efficiently heating and cooling large and small scale buildings. GCHP systems reject heat to the subsurface during the warm summer months and extract heat from the subsurface during the cold winter months using a BHE. The effects of seasonal and diurnal outdoor ambient temperature changes diminish with depth below the ground surface, and subsurface temperatures remain relatively stable below a certain depth (Florides et al. 2011), typically 5 to 8 meters (Piscaglia et al., 2016), and is attributed to the high thermal inertia of soil and rock (Florides and Kalogirou, 2007).

GCHP systems are becoming more common throughout the world due to their efficiency. From 1994 to 2004, the use of these systems increased 10 percent annually in about 30 countries with most of the growth in the United States and Europe (Lund et al. 2004). Large industrial GCHP systems are also becoming more common. For example, Ball State University (BSU) in Muncie, Indiana completed a large industrial GCHP system consisting of 3,600 boreholes drilled to depths of 122 to 152 m, in the spring of 2012. It was considered the largest in the nation at the time of its construction, and was used to heat and cool 47 buildings (511,000 m^2 [square meters]) on campus. This allowed the University to take its fossil-fuel boilers offline which reduced CO_2 emissions by 77,000 metric tons and created an annual savings of 2 million US dollars (BSU, 2016).

Stockton College in southern New Jersey completed a large GCHP system in 1994. The BHE consists of 400 boreholes drilled to a depth of 130 m (Taylor et al., 1997). The well fields at Stockton College extend to similar depths as other large scale systems although the geology is much different. The boreholes extend through the Kirkwood-Cohansey aquifer system, which is generally characterized as variable with interbedded layers of sands, gravels, and clays, and is a principle unconfined aquifer system in the New Jersey Coastal Plain (Zapecza, 1989). The BHE at Stockton College extends into the Rio Grande water bearing zone at 96 to 107 m which was expected to have higher specific heat and thermal conductivity. The flow of groundwater was also expected to enhance heat transfer to and from the BHE (Taylor et al., 1997). The construction of the system initially cost 5.1 million dollars but much of this was covered by grants and utility rebates. The annual savings of the GCHP system is $400,000 in fuel and maintenance cost which includes a reduction in the use of electricity and natural gas as well as a large reduction in CO_2 emissions (Cross, 2011). Other institutions across the country that have implemented these large geothermal systems include Lake Land College in Illinois, Drury University in Missouri, Harvard University in Massachusetts, Feather River College in California, Hamilton College in New York, Northland College in Wisconsin, Yale University in Connecticut, and others (Cross et al., 2011).

The Missouri University of Science and Technology (S&T) completed a large GCHP system in 2014 in an effort to reduce heating and cooling costs and water use. The S&T GCHP system is one of the largest systems of its kind in the United States. The system was designed to replace an aging heating and cooling system which had a nearly 70 year old power plant that provided steam using coal and woodchip fueled boilers. The GCHP system BHE consists of 789 closed loop wells between 122 and 134 m deep. The wells serve three primary campus GCHP plants and one satellite plant at the 42,178 m^2 Gale Bullman Multi-purpose Building. Each plant consists of heat recovery chillers (500 tons), supplementary cooling towers, and gas-fired boilers which help to heat and cool the campus buildings during extreme temperatures. The new system has allowed S&T to reduce annual energy consumption by 57 percent, CO_2 emissions by 23,000 metric tons per year, and water usage by 85 million liters per year (Missouri University of Science and Technology, 2016).

This paper describes the impact of groundwater flow on the 144 well BHE that serves the Gale Bullman Multi-purpose Building. The BHE covers an area of 2,860 m^2 and differs from the BHE at Stockton College in that it was installed in nearly 122 m of karstic dolomite and sandstone which is part of the Ozark Aquifer. The BHE extends through residuum (6 m thick), Jefferson City Formation (46 m; dolomite), Rubidoux

Formation (37 m; dolosmite and sandstone), and the Gasconade Formation (34 m; dolomite and cherty dolomite). It is important to note that the geology for the system at BSU was typically limestone and shale. Well log #421719 for a well drilled in 2009 on the BSU campus indicated clay (6.7 m) at the surface, followed by gravel (2.1 m), clay (8.8 m), limestone (43.3 m), and shale (61.3 m) at the bottom of the borehole (IDR, 2009).

There have been multiple studies that have considered the effects of groundwater on small GCHP systems. Groundwater can affect the BHE performance of a GCHP system in two general ways.

1. The presence of groundwater at a BHE can affect the thermal properties of the surrounding geologic material, whether it is rock or soil, by increasing thermal conductivity (Robertson, 1988; Mohamed et al., 2015).
2. Groundwater flow has also been shown to enhance heat transfer to and from BHEs (Chiasson et al., 2000; Lee and Lam., 2007 and 2008; Fan et al., 2007).

Mohamed et al. (2015) designed a bench-scale GCHP system to characterize the effects of both vertical groundwater flow and fluctuations in groundwater levels. The model consisted of a one cubic meter tank with a horizontal heat exchanger centered in the tank and surrounded by sand. The tank was equipped with a series of controls and a drainage system to manipulate the water level within the tank. A total of 26 type-t thermocouples were used to monitor the temperature of the heat exchanger, surrounding soil, and the inlet and outlet temperature of the heat exchanger. Fluid was moved through the heat exchanger using a parasitotic pump under different water level conditions and simulated precipitation scenarios. Mohamed et al. (2015) concluded that both groundwater level and simulated precipitation had a significant effect on the heat transfer between the heat exchanger and the surrounding sand. Thermal conductivity of the sand when it had residual saturation exhibited a five–fold increase when compared to dry sand. Heat recovery was four times greater when the water level was above the heat exchanger when compared to dry sand. The simulated precipitation was also shown to enhance the heat recovery and the degree to which the heat was recovered was dependent on the intensity of the simulated precipitation (Mohamed et al. 2015).

Groundwater flow has also been shown to affect the performance of BHEs. In several studies, Molina-Giraldo et al., 2011, Diao et al., 2004, and Fan et al., 2007 have shown that groundwater flow plays a significant role in the performance of BHEs by incorporating groundwater flow into GCHP models. Chiasson et al., (2000) showed that groundwater flow significantly enhances heat transfer in media with high hydraulic conductivity such as sands, gravels, and fractured bedrock.

Despite a growing body of research on smaller GCHP systems and simulated models, most large industrial GCHP systems are relatively recent constructions and do not have extensive operating histories. Stockton College completed a system in 1994, Lake Land College completed two systems in 2008, and BSU completed a system in 2009 (Cross et al., 2011). S&T's GCHP system is one of the most recent being completed in 2014. Little is understood about how long-term changes in groundwater levels and flow affect the performance of large-scale BHEs. Site hydrogeology is typically given little attention when designing large-scale GCHP systems (Florea et al. 2016; Smith et al., in review). Thermal response tests (TRTs) are generally conducted once resulting in a snapshot of the effective thermal conductivity of surrounding geologic materials. The effective thermal conductivity is essential in the design of large-scale GCHP systems. A single TRT does not take into account changes in levels of groundwater flow which may not change significantly during the course of a 48 hour TRT. Smith et al. (in review) showed that the performance of large-scale BHEs is significantly affected by long-term seasonal changes in the saturation of the surrounding aquifer. The effectiveness of a large-scale BHE can be as high as 88 percent when the saturation of the aquifer is at its highest and as low as 38 percent when the saturation of the aquifer is lowest. This study showed that the heat transfer rate between the BHE and the aquifer can be twice as large during periods of high saturation compared to low saturation. Smith et al. (in review) concluded that long-term changes in the hydrogeology should be properly characterized in order anticipate changes in the performance of large-scale BHEs. There has been little research characterizing the performance of the new large-scale BHEs with significant groundwater flow. There is also little research that compares both the effects of aquifer saturation and groundwater flow together. It has been shown that both have an effect on the performance of BHEs (Smith et al. in review, Mohamed et al. 2015, Molina-Giraldo et al., 2011, Diao et al., 2004, Chiasson et al., 2000, and Fan et al., 2007). This study examines the performance of a large-scale GCHP system BHE given changes in groundwater flow as a result of periodic pumping of a large nearby municipal well.

2. METHODS

2.1 SITE DESCRIPTION

The study area is located at the Gale Bullman Multipurpose building on the S&T campus in Rolla, Missouri. The study focuses on the 144 well BHE shown in Figure 1 which is a subsystem of the GCHP system for the building. The 144 boreholes for the BHE are drilled to a depth of 122 m below the land surface and generally extend through residuum (6 m thick) at the surface, the Jefferson City Formation (46 m; dolomite), the Rubidoux Formation (37 m; dolomite and sandstone), and the Gasconade Dolomite (34 m; dolomite and cherty dolomite). The three formations underlying the residuum are excellent producers of water and are part of the Ozark Aquifer which is a major source of water for parts of Missouri, Kansas, Oklahoma, and Arkansas (Imes and Emmet, 1994; Vandike, 1992; Miller and Vandike, 1997). The city of Rolla has 18 municipal wells in use that are all cased to the Gasconade formation. Overall, public supply groundwater withdrawals in Rolla and the surrounding county were approximately 12.3 million liters per day in 2010 (USGS, 2014) which has trended upward as the student and general population increases. A temperature monitoring well was drilled 6 m west and centered on the 144 borehole wellfield as shown in Figure 1. The temperature monitoring well was used to monitor the ambient temperature of the aquifer adjacent to the BHE.

The large city municipal well observed in this study is located approximately 335 m south of the BHE. The pump capacity of the well is approximately 2,135 liters per minute (PDWS Reports, 2016). The well was drilled to a depth of 350 m in 1947 and had a static water level of approximately 75 m below land surface. The casing of the city well extends from the surface to 85 m which is 3 m into the Gasconade dolomite (MDNR, 1947) and the BHE also extends through 34 m of that formation. The BHE and the city well are both open to the Gasconade dolomite.

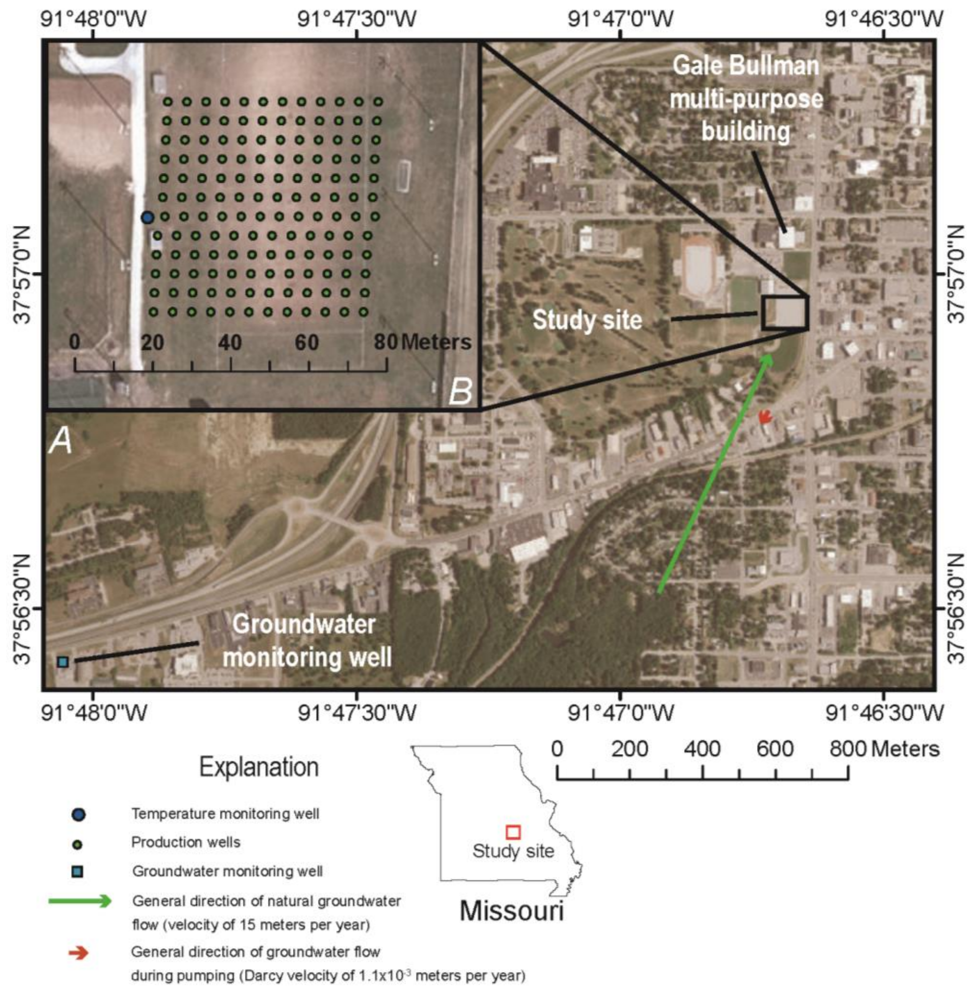

Figure 1. Location of study site in Rolla, Missouri, 2015-16 (A) and plan view of the borehole heat exchanger (B; Smith et al., in review).

2.2 INSTRUMENTATION

Eight Omega™ SA2C-T (type-t) thermocouples were installed at 15 m intervals starting at 15 m below the surface on 3.8 centimeter diameter high-density polyethylene (HDPE) pipe that extended 122 m from the ground surface to the bottom of the borehole. Florides et el., (2011) also installed Omega thermocouples attached to u-tubes at multiple depths, but used type-k rather than type-t, although both are acceptable for the temperature ranges found in typical BHEs. The SA2C-T thermocouples are self-adhesive and specifically designed for curved surfaces such as pipes. Heavy 16-gauge thermocouple extension wire was used to connect the thermocouples to the data loggers to reduce resistance over the 15m to 122 m distance from the data logger to the individual thermocouples. Two Campbell Scientific CR10X data loggers (August 2015 to December 2015) and two Campbell Scientific CR10 data loggers (January 2016 to July 2016) were used to take and record the thermocouple readings and were located inside of a weather-proof box which was in an underground concrete enclosure. Temperature data was recorded every 60 minutes (min) from September 2015 through December 2015 and every 30 min from January 2016 through July 2016 as reported in (Smith et al., in review).

The static water level before pumping the municipal well, the residual water level after pumping, the time when pumping began and ended and pumping duration was recorded by the well operator using airline measurements. This data was provided by the city of Rolla for this study.

The S&T Physical Facilities Department monitors multiple parameters of the whole campus system. Physical Facilities provided system data for the study. That data included the temperature of the water entering the BHE, the temperature of the water leaving the BHE, and the flowrate. These parameters were measured at 15 min intervals.

2.3 DATA ANALYSIS

The effectiveness of the BHE was the foundation for the study and how the effectiveness changed as the flow of groundwater changed due to the intermittent operation of the nearby municipal well was the key aspect. The effectiveness was calculated using Equation 1(Incropera and DeWitt, 2002) which is the ratio of the instantaneous heat transfer rate (h) over the maximum theoretical heat transfer rate (h_m) of the BHE.

$$\varepsilon = \frac{h}{h_m} \tag{1}$$

The instantaneous heat transfer rate (h) was calculated using Equation 2 (Incropera and DeWitt, 2002). This is the actual rate that energy is rejected from the BHE or gained by the BHE as it interacts with surrounding rock, soil, and groundwater calculated from the temperatures and flowrate of the circulating water. T_i is the temperature of the water entering the BHE, T_o is the temperature of the water leaving the

BHE, C_p is the specific heat capacity of water, ρ_w is the density of water, and the flow rate of the water in the ground loop is q. T_i, T_o, and q were measured by S&T physical facilities personnel as mentioned previously. The specific heat capacity (C_p) used in the study was 4.18 joules per gram change in temperature (Celsius) and the density of water (ρ_w) used in the study was 1,000 kilograms per cubic meter. It is assumed that the changes in these two parameters are insignificant considering the range of temperatures of the circulating water.

$$h = (T_i - T_o)C_p\rho_w q \quad (2)$$

The maximum theoretical heat transfer rate (h_m) was calculated using Equation 3 (Incropera and DeWitt, 2002). This is the energy transfer that is possible based on the temperature of the aquifer. The energy of the water in the BHE will theoretically equilibrate to the aquifer as energy moves to or from the aquifer. The temperature of the water in the BHE and the aquifer generally never reach equilibrium in that the water temperature reaches an equal temperature to that of the aquifer and the scale of the aquifer is much larger than the BHE. This is controlled by how efficiently the energy moves, which is by conduction and convection, and is dependent on the thermal and flow properties of the surrounding geologic materials. The specific heat capacity (C_p) and the density of water (ρ_w) values used in Equation 2 were also used in Equation 3. The maximum theoretical heat transfer rate (h_m) also used identical values for T_i and q used in Equation 2 for calculating ε. The single difference in h and h_m is the replacement of T_o with T_a. T_a and is simply the temperature of the aquifer in proximity to the BHE. T_a is the mean temperature of the instantaneous temperature measurements of the eight thermocouples in the temperature monitoring well which were measured at the same time as the T_i, T_o, and q.

$$h_m = (T_i - T_a)C_p\rho_w q \quad (3)$$

The effectiveness (ε) as calculated in Equation 1 is a measure of how efficient the BHE is operating and is commonly used for basic heat exchanger evaluation (Incropera and DeWitt, 2002). For example, as the water entering the BHE loses energy to or gains energy from the surrounding aquifer it generally leaves the BHE having never completely cooled (energy loss) or warmed (energy gain) to the temperature of the aquifer. The more the water in the BHE cools or warms to the aquifer temperature, the higher the effectiveness of the BHE which means higher efficiency.

The overall groundwater velocity through the BHE was calculated using Darcy's Law (Equation 4) where Q is the discharge, k is hydraulic conductivity, $\frac{dh}{dl}$ is the gradient, and A is the cross sectional area of the aquifer.

$$Q = \frac{dh}{dl} kA \tag{4}$$

The hydraulic conductivity value of 3,900 m/yr (meters per year) was chosen to calculate groundwater velocity. This value was the average of a range of hydraulic conductivities used by Immes and Emmett (1994) for the lateral hydraulic conductivity in a groundwater model of the Ozark Aquifer for the area containing this site. This is consistent with ranges of hydraulic conductivities for karst limestone (Freeze and Cherry, 1979). Groundwater flow in the Gasconade dolomite and overlying Rubidoux formation has been found to be dominated by fracture flow in nearby sites (Kleeschulte and Imes, 1997). The site in this study is also centered within a large area identified as karst (Epstein et al., 2002). A porosity value of 0.1 was also used in the calculation of groundwater velocity which is consistent with porosity ranges for karst (Freeze and Cherry, 1979). The groundwater gradient across the BHE for the Gasconade dolomite formation was calculated before and after pumping of the municipal well. The gradient before pumping was calculated using Vandike's (1992) potentiometric map of the Rolla, Missouri area. The distance between contour lines was divided by the contour interval. The groundwater gradient after pumping was calculated using the Theis Equation (Equation 7).

$$h_0 - h = \frac{Q}{4\pi T} w(u) \tag{5}$$

$$Where\ w(u) equals\ the\ well\ function$$

A transmissivity value of 3.4 m^2/s was estimated using the specific capacity of the well. The average specific capacity for all the 24 hour pumping events for well 5 from January 2014 to June 2016 was 103 l/min/m which is the pumping rate divided by the total drawdown over the 24 hour period. Transmissivity can be estimated as approximately 1,000 times the specific capacity for unconfined aquifers, and 2,000 times the specific capacity for confined aquifers (Walton, 1962) for 24 hours of consistent pumping. The gradient across the BHE after pumping was calculated as the difference in the drawdown ($h_0 - h$) at the points of the BHE nearest (436 m) and farthest (503 m) from the pumping well divided by the distance between the two points (67 m).

Statistical analysis for groups of calculated effectiveness during the BHE's operation in the presence of differing groundwater flow conditions was completed using the Kruskal-Wallis Test. This test was used to compare whether the effectiveness values grouped by differing groundwater flow originate from the same distribution overall (Kruskal and Wallis, 1952). The Dwass-Steel-Chritchlow-Fligner Pairwise Comparison was used to compare the individual groups of effectiveness values and if they were significantly different from each other.

3. RESULTS AND DISCUSSION

The general groundwater gradient across the BHE within the Gasconade dolomite is approximately 0.009 with groundwater moving approximately northward, away from the municipal well. This was calculated using Vandike's (1992) potentiometric map of the Rolla area and dividing the contour interval by the distance of the groundwater contour lines on either side of the BHE. Multiplying the gradient by hydraulic conductivity value of 3,900 m/yr (Immes and Emmett, 1994) equals a general northward groundwater flow of 15 m/yr. The typical drawdown resulting from 24 hours of pumping at the municipal well was 3.81 cm at the BHE's nearest point from the well (radius equal 436 m) and 3.75 cm at the BHE's farthest point from the well (radius equal 503 m). The calculated groundwater flow was approximately 1.1×10^{-3} m/yr southward (table 1) which is so low that it may be considered zero flow.

Table 1. Calculated groundwater gradient and velocities directly before and after pumping.

	Gradient	Groundwater velocity (m/yr)	General direction
Before pumping	$4.0x10^{-2}$	15	north
During pumping	$2.8x10^{-6}$	$1.1x10^{-3}$	south

Fan and others (2007) used the groundwater velocities of 60, 30, and 15 m/yr to understand the effect of groundwater flow on BHEs in their mathematical models. This velocity range was sufficient to characterize the effect of velocity on the S&T BHE. The velocities in this study of 15 m/yr and essentially zero are comparable to those used by Fan and others (2007) indicating that these velocities are sufficient to characterize the effect of groundwater velocity on the BHE observed in this study (Table 1).

The median calculated effectiveness 24 hours before pumping (0.46), 24 hours during pumping (0.46), and 24 hours after pumping (0.43) for all effectiveness values as shown in Table 2 does not appear to noticeably change when compared to fluctuations due to changes in the saturation of the aquifer as shown by Smith et al., (in review). The effectiveness of this BHE tends to range from 0.88 during periods of high saturation of the aquifer to 0.38 during periods of low saturation (Smith et al., in review)

Smith et al. (in review) has shown that an effectiveness value of 0.5 tends to lie between the bimodal effectiveness of the BHE which may be caused by changes in the saturation of the aquifer. This 0.5 value may coincide with a particular saturation, and if exceeded tends to result in very high effectiveness, and conversely, values below 0.5 tend to indicate very low effectiveness. The median effectiveness shows a decrease from 0.70 (24 hours before pumping) to 0.68 (during 24 hours of pumping) followed by an increase to 0.73 (24 hours after pumping) when examining effectiveness values greater than 0.5. The median effectiveness shows an increase from 0.38 (24 hours before pumping) to 0.41 (during 24 hours of pumping) followed by a decrease to 0.39 (24 hours after pumping) when the median effectiveness values are less than 0.5.

Overall, the trend lines for all effectiveness values greater than 0.5 for the BHE during and after pumping show the greatest increase in effectiveness over time and are shown in Figures 2E and 2F. The overall effectiveness of the BHE before and after pumping tends to remain flat when plotted against time (Figures 2A, 2C) although the effectiveness shows a decrease with time during pumping (Figure 2B). The effectiveness also tends to have a bimodal distribution which was also reported by Smith et al., (in review). The effectiveness before, during, and after pumping for all effectiveness values less than 0.5 tends to remain flat with time (Figures 2G, 2H, 2I). The effectiveness is shown to increase both during pumping and after pumping (Figures 2E, 2F) but tended to remain flat before pumping (Figure 2D) for all effectiveness values greater than 0.5 which may represent a more saturated aquifer as shown by Smith et al. (in review).

Table 2. The median and mean effectiveness of the borehole heat exchanger 24 hours before pumping, 24 during pumping, and 24 hours after pumping of the municipal well for different groups of effectiveness ranges.

	24 hours before pumping	24 hours during pumping	24 hours after pumping
All cases with associated flowrate of BHE greater than 1.52 cubic meters per minute			
n	306	407	406
Median	0.46	0.46	0.43
Mean	0.50	0.55	0.52
All cases with associated flowrate of BHE greater than 1.52 cubic meters per minute and effectiveness greater than 0.5			
n	131	192	161
Median	0.70	0.68	0.73
Mean	0.82	0.70	0.73
All cases with associated flowrate of BHE greater than 1.52 cubic meters per minute and effectiveness less than 0.5			
n	175	215	245
Median	0.38	0.41	0.39
Mean	0.27	0.41	0.38

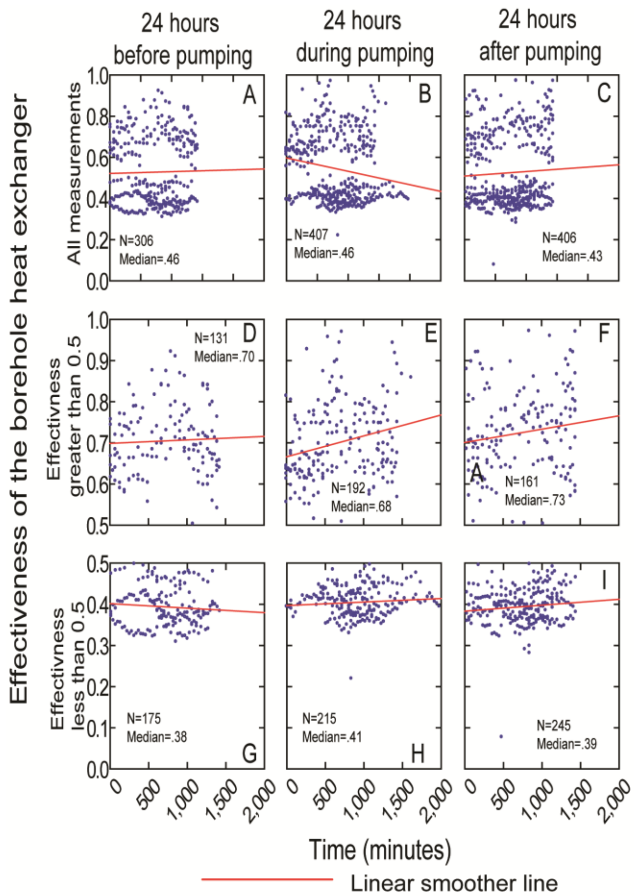

Figure 2. A comparison of the borehole calculated effectiveness 24 hours before pumping, 24 hours during pumping, and 24 hours after pumping over time.

A comparison of the effectiveness of the BHE when grouped by 24 hours before the start of pumping, during pumping, and 24 hours after pumping using the Kruskal-Wallis Test shows that there is a significant difference (all p-values less than 0.05 for tests 1, 5, and 9) between the groups with all effectiveness values, for effectiveness less than 0.5, and greater than 0.5 (Table 3). Pairwise comparison for each of the three groups (24 hours before pumping, 24 hours during pumping, and 24 hours after pumping) for all three groups of effectiveness values (all effectiveness values, effectiveness greater than 0.5, and effectiveness less than 0.5) shows a significant difference (p-value less 0.05) for most groups using the Dwass-Steel-Chritchlow-Fligner Pairwise Comparison with two exceptions. Tests 4 and 12 were the only pairwise comparison that resulted in a p-value greater than the 0.05 (0.7 for test 4 and 0.38 for test 12). Test 4 compared the effectiveness of the BHE during pumping to the effectiveness 24 hours after pumping for all effectiveness values while test 12 compared the same to groups with effectiveness greater than 0.5 which generally indicates a more saturated aquifer for the site (Smith et al., in review).

A comparison of all six groups (Table 4) using the Kruskal-Wallis Test and the Dwass-Steel-Chritchlow-Fligner Pairwise Comparison shows similar results with few exceptions. Groups BP; <0.5 and BP; >0.5, which are the two groups of effectiveness values during the 24 hours before pumping for effectiveness less than 0.5 (BP; <0.5) and effectiveness greater than 0.5 (BP; >0.5) are the only two groups that are significantly different from all other groups in all comparisons. Groups BP; <0.5 and BP; >0.5 are also the groups that the data for calculating the effectiveness was recorded during periods of the greatest groundwater flow (15 m/yr; Table 1) based on Vandike's (1992) model. Tests 7 (Comparison of groups DP; <0.5 and AP; <0.5) and 16 (Comparison of groups DP; >0.5 and AP; >0.5) both have p-values much greater than 0.05 indicating that there is no sigificant difference between the two groups compared in both tests. These tests compared the calculated effectiveness during pumping and after pumping where groundwater flow was twice reversed (when pumping began and when pumping ended) and groundwater flow was calculated to be much less (during pumping only; 1.1x10-3 m/yr; Table 1). There is insufficient data to calculate the groundwater velocity of groundwater after pumping ceased, but the groundwater flow most likely reversed from 1.1×10^{-3} m/yr southward to 15 m/yr northward as the well recovered. The nearby Missouri Groundwater Observation Network well located 1.3 miles from the BHE tends to fully recover in about two to three days after nearby pumping events. (USGS, 2017). A comparison of the median effectiveness of the BHE to the saturation of the aquifer based on the nearby Missouri Groundwater Network Observation well (Figure 1) before, during, and after pumping, shows that the effectiveness of the BHE tends to increase as the saturation of the aquifer increases (Figure 3). The median effectiveness was generally greater than 0.5 when the saturation of the aquifer was greater than 0.513 as shown in Figure 3. This is also the case when the groundwater flow across the BHE is greatest (24 hours before pumping; 15 m/yr; Table 1) and when it is most likely the least (during

Table 3. Results of the Kruskal-Wallis Test and Dwass-Steel-Chritchlow-Fligner Test comparing the effectiveness of the borehole heat exchanger 24 hours before pumping (BP), 24 during pumping (DP), and 24 hours after pumping (AP) of the municipal well for different groups of effectiveness ranges.

Test	Group A	Group B	Statistic	p-value
All cases with associated flowrate of BHE greater than 1.52 cubic meters per minute				
Kruskal-Wallis Test				
1	All 3 group comparison		15.3	0.00
Dwass-Steel-Chritchlow-Fligner Test				
2	BP	DP	23.6	0.00
3	BP	AP	21.4	0.00
4	DP	AP	-3.1	**0.07**
All cases with associated flowrate of BHE greater than 1.52 cubic meters per minute and effectiveness less than 0.5				
Kruskal-Wallis Test				
5	All 3 group comparison		15.3	0.00
Dwass-Steel-Chritchlow-Fligner Test				
6	BP	DP	15.6	0.00
7	BP	AP	9.2	0.00
8	DP	AP	-6.6	0.00
All cases with associated flowrate of BHE greater than 1.52 cubic meters per minute and effectiveness greater than 0.5				
Kruskal-Wallis Test				
9	All 3 group comparison		8.6	0.01
Dwass-Steel-Chritchlow-Fligner Test				
10	BP	DP	17.2	0.00
11	BP	AP	14.0	0.00
12	DP	AP	-1.9	**0.38**

24 hours before pumping = BP

24 hours of pumping = DP

24 hours after pumping = AP

Table 4. Results of the Kruskal-Wallis Test and Dwass-Steel-Chritchlow-Fligner Test comparing all 6 groups of effectiveness simultaneously grouped by 24 hours before pumping, 24 during pumping, and 24 hours after pumping of the municipal well and effectiveness ranges.

Test	Group A	Group B	Statistic	p-value
		Kruskal-Wallis Test		
1	All 6 group comparison		15.3	0.00
		Dwass-Steel-Chritchlow-Fligner Test		
2	BP; <0.5	DP; <0.5	8.69	0.00
3	BP; <0.5	AP; <0.5	15.10	0.00
4	BP; <0.5	BP; >0.5	27.76	0.00
5	BP; <0.5	DP; >0.5	18.21	0.00
6	BP; <0.5	AP; >0.5	18.65	0.00
7	DP; <0.5	AP; <0.5	0.98	**0.98**
8	DP; <0.5	BP; >0.5	15.78	0.00
9	DP; <0.5	DP; >0.5	7.85	0.00
10	DP; <0.5	AP; >0.5	11.48	0.00
11	AP; <0.5	BP; >0.5	18.81	0.00
12	AP; <0.5	DP; >0.5	2.23	**0.61**
13	AP; <0.5	AP; >0.5	9.45	0.00
14	BP; >0.5	DP; >0.5	-12.65	0.00
15	BP; >0.5	AP; >0.5	-4.18	0.04
16	DP; >0.5	AP; >0.5	3.02	**0.27**

24 hours before pumping and effectiveness less than 0.5 = BP; <0.5

24 hours of pumping and effectiveness less than 0.5 = DP; <0.5

24 hours after pumping and effectiveness less than 0.5 = AP; <0.5

24 hours before pumping and effectiveness greater than 0.5 = BP; >0.5

24 hours of pumping and effectiveness greater than 0.5 = DP; >0.5

24 hours after pumping and effectiveness greater than 0.5 = AP; >0.5

pumping; $1.1x10^{-3}$ m/yr; Table 1.) as shown below. The median effectiveness never exceeded 0.5 when the aquifer saturation was less than 0.513.

Smith et al. (in review) reported changes in the effectiveness of the BHE ranging from 0.88 to 0.38. Effectiveness in the highest saturation ranges showed a strong relation to aquifer saturation. The median effectiveness decreased with successive decreases in aquifer saturation (0.88 effectiveness for percent saturation of 55.0–53.8; 0.73 effectiveness for percent saturation of 53.8–52.5; 0.43 effectiveness for percent saturation of 52.5–51.3) as reported by Smith et al. (in review). The changes in median effectiveness due to changes in groundwater flow tended to be much less and typically were not greater than 0.05. The largest change in the median effectiveness appeared to be from 0.68 during pumping to 0.73 after pumping when the aquifer was most saturated (Table 1).

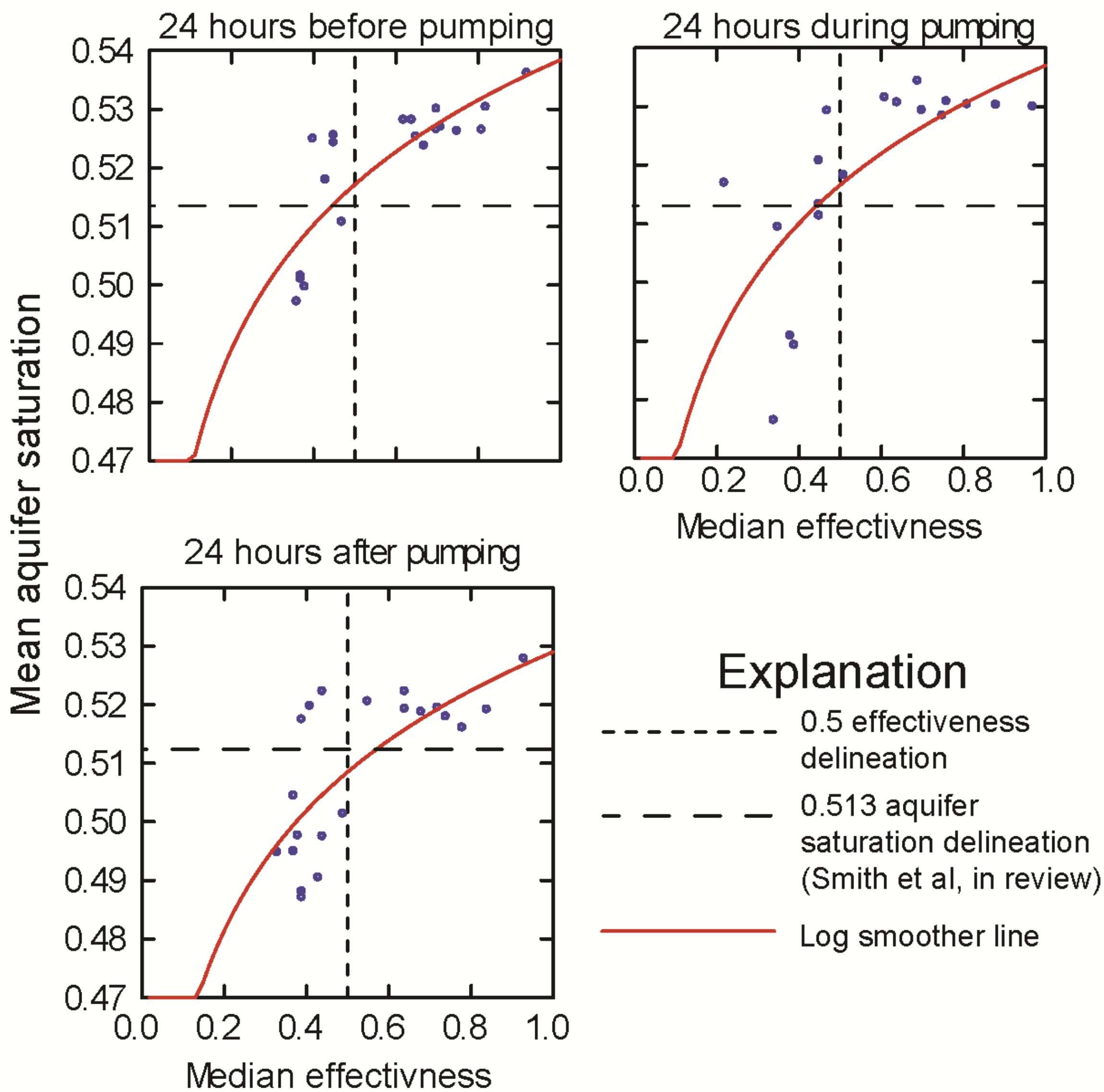

Figure 3. The mean saturation of the aquifer compared to the median effectiveness 24 hours before, during, and 24 hours after pumping for each 24 hour pump operation through September 2015 to July 2016.

4. CONCLUSIONS

Overall, the effectiveness of the S&T BHE tends to be slightly enhanced by existing groundwater flow when the aquifer is highly saturated. The operation of the nearby municipal well tends to reverse the direction of the groundwater flow across the BHE which also significantly decreases the groundwater velocity. This tends to cause a small decrease in the effectiveness by both reversing the flow and decreasing the groundwater velocity. This is more evident during periods of greater aquifer saturation.

Changes in the effectiveness of the BHE as a result of changes in groundwater flow were much smaller overall when compared to changes in the saturation of the aquifer. This is also true when characterizing the BHE effectiveness before, during, and after pumping based on the saturation of the aquifer. Changes in the saturation of the aquifer have a greater influence on the effectiveness of the S&T BHE when compared to groundwater flow. Characterizing both seasonal changes in the saturation of the aquifer and groundwater flow will help to predict the long term performance of a GCHP system.

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III. CHARACTERIZING LITHOLOGICAL EFFECTS ON LARGE SCALE BOREHOLE HEAT EXCHANGERS DURING CYCLIC HEATING OF THE SUBSURFACE

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ABSTRACT

This paper presents the results of a study where subsurface temperatures were monitored adjacent to the u-tube of a central borehole of a large scale 144 borehole heat exchanger (BHE) at multiple depths. This was an effort to develop a method to characterize the variability of thermal properties of the various lithological units surrounding the BHEs of large scale ground coupled heat pump systems during the operation of the system. Saturation of the units and lithology was shown to affect the performance of the BHE resulting variable temperature fluctuations and heat flux at different depths within the borehole. Median heat flux tended to increase with decreasing temperature ranges measured by the sensors. The lowest median heat flux was in the location nearest to the surface in the least saturated zone. In the more saturated zone, the highest median heat flux were at locations where the lithological units were composed of

75 percent or greater dolomite while the lowest median heat flux where in lithological units composed of 30 percent or greater chert.

Keywords: Geothermal system; borehole heat exchanger; groundwater; groundwater flow; geothermal energy; ground source heat pump; lithology.

1. INTRODUCTION

The use of ground coupled heat pump (GCHP) systems is increasing rapidly throughout the United States. Boyd et al. (2015) estimated 8 percent annual growth with 80,000 units installed per year with most of the growth taking place in the midwest and eastern regions of the country. This growth has been fueled by rising energy costs coupled with consumer tax credits for installing the systems (Boyd et al., 2015).

The effectiveness of these systems is due to their ability to remove heat energy from buildings during the warm summer months and store that energy in subsurface which remains a relatively constant temperature year round. Likewise, they are able to extract energy from the subsurface during the cold winter months to heat buildings. GCHP systems are efficient at transporting heat energy between buildings and the subsurface through the use of heat exchangers ground heat exchangers. There are many types of ground heat exchangers but they are generally classified as open- or closed-looped (Florides and Kalogirou, 2007). Open-loop ground heat exchangers are open systems that circulate groundwater through the system and then reject that heated or cooled water back into the ground. Closed-loop ground heat exchangers are closed systems and circulate water through the system with no mass exchange with the present groundwater. These systems can come in many different configurations from shallow to deep; and can be placed vertically or horizontally (Florides and Kalogirou, 2007). Large industrial systems generally have deep closed loop borehole heat exchangers (BHE) that extend tens of meters into the soil or bedrock and are made up of multiple boreholes.

The industrial use of GCHP systems on institutional scales have also increased sharply in recent times as colleges and business have brought GCHP systems online for heating and cooling. In 1994, Robert Stockton College in New Jersey was one of the earliest institutions to bring a large scale GCHP system online. The system consists of 400 bore holes drilled to depths of 130 meters (m) and was drilled into the local aquifer (Taylor et al., 1997). Ball State University (BSU) completed a large scale GCHP system in 2012. This system was the largest of its kind at the time of construction. The system consists of 3,600 boreholes drilled to depths of 122 to 152 m (BSU, 2016). These BHE's can commonly extend through the unsaturated zone and into the saturated zone (Choi et al., 2011).

Despite the increase in the construction of large-scale GCHP systems only a small fraction of the construction cost is used to characterize the geohydrology of the site or monitor the long term effects that these large systems have on the aquifer (Florea et al., 2016). The industry generally relies on a single thermal response test (TRT) which is used to characterize the effective thermal conductivity of the subsurface (Sanner et al., 2005). However, a single TRT does account for long term changes in the groundwater saturation and flow (Smith et al., in review). There is a growing body of research showing the important role that groundwater has on large GCHP systems but more specifically, the BHE. The presence of groundwater increases the overall thermal conductivity of the rock or soil (Clauser and Huenges, 1995; Robertson, 1988, Albert et al., 2016). Mohamed et al. (2015) constructed a bench-scale GCHP system model which showed that heat flux between the heat exchanger and the model's sandy soil was enhanced when the water level was higher. Smith et al. (in review) studied the operation of a large scale GCHP system in a major karstic aquifer. Data was collected during nearly a year of operation of the system which saw periods of high and low saturation in the aquifer. The study showed that the effectiveness of the GCHP system's BHE during periods of high saturation was nearly 90 percent and was as low as 38 percent during periods of the lowest saturation. Smith et al. (in review) reported that water levels recorded in a nearby groundwater observation well has shown a declining trend in the saturation of the aquifer since 1968. The study showed the importance of characterizing the long term and seasonal changes in the saturation of the aquifer (Smith et al., in review).

Groundwater flow has also been shown to affect the performance of GCHP systems (Lee and Lam., 2007; Fan et al., 2007; Smith and Elmore, in review; Chiasson et al., 2000). Lee and Lam (2007) demonstrated that borehole configuration was important when considering groundwater flow. Computer simulations of a GCHP system performance using different thermal loading profiles and different BHE configurations (width and length ratios of 1:1, 1:2, and 2:3) were conducted to compare the performance of different BHE configurations under groundwater flow. The square BHE configuration was less likely to be affected by groundwater flow direction (Lee and Lam., 2007). Conversely, by knowing the direction of groundwater flow, the configuration of the BHE could be optimized to increase the effective surface area of the BHE.

Fan et al. (2007) developed a dynamic mathematical model to account for groundwater advection and its influence on a BHE. Simulations of the model showed that the presence of groundwater significantly influenced the heat flux between the BHE and the surrounding soil. Changes in the velocity of the groundwater also had a noticeable effect on the heat flux between the soil and the BHE. Using groundwater velocities of zero, 15, 30, and 60 meters per year (m/yr), Fan et al. (2007) reported that heat flux between the soil and the BHE increased with increasing groundwater velocity and suggested groundwater flow be considered in the design of GCHP systems.

Smith and Elmore (in review) observed the operation of the BHE of large scale GCHP system in fractured rock. The groundwater velocity was calculated based on a groundwater model of the area (Vandike, 1992) and pumping data from a large nearby municipal well. The study showed that an existing steep groundwater gradient of 4.0x10-2 was reversed in the opposite direction while also decreasing to 2.8x10-6 which greatly decreased the groundwater velocity from 15 to nearly zero m/yr. Smith and Elmore (in review) reported a significant decrease in the effectiveness of the GCHP system's BHE.

Chiasson et al. (2000) used the dimensionless Peclet number (Domenico and Schwartz, 1990) and a finite-element numerical groundwater flow and heat transport model to simulate the effects of groundwater flow on a single u-tube BHE in differing types of geologic material. Based on simulations and analysis of the Peclet number, Chiasson et al. (2000) reported that groundwater flow only has a significant effect on geologic materials with high hydraulic conductivities such as coarse-grained soils and fractured rock. Further simulation of TRT in different flow conditions showed that the resulting thermal conductivity values of the geologic material were artificially high with groundwater flow.

Smith and Elmore (in review) monitored the performance of a large scale BHE for nearly a year which was in the vicinity of a nearby active municipal well. The groundwater flow was northward at 15 meters per year but the periodic operation of the municipal well reversed the groundwater flow and significantly reduced velocity. The effectiveness of the BHE was found to be greater before and after the pumping of the municipal well.

Chiasson et al. (2000) used a finite-element numerical model to simulate the effects of groundwater flow on a single closed loop BHE. The study showed that groundwater significantly enhanced the heat flux when in materials with high hydraulic conductivity such as sands, gravels, and fractured rock (Chiasson et al., 2000).

A third and less explored factor that may affect the performance of BHEs is the lithology. Previous studies (Robertson, 1988; Siliski, 2014; Albert et al., 2016; Sass and Götz, 2012) have shown that thermal properties can vary with rock type. However, little attention is given to lithology as the industry standard TRT treats the underlying lithology as homogeneous (Florea et al., 2016). Research on the lithology surrounding BHEs of large scale GCHP systems at Stockton College (Taylor et al., 1997), BSU (Siliski, 2014), and the Missouri University of Science and Technology (S&T; Smith et al., in review) show that the BHEs generally extend through multiple rock and soil units with different thermal and hydraulic properties.

This paper presents a new method for characterizing the performance of different rock or soil units based on heat flux during the operation of the system. A series of thermocouples were installed to monitor the temperatures at different locations along a central borehole of a 144 well BHE (Figure 1). The effects of outside ambient air decrease with depth. Florides and Kalogirou (2007) have shown that subsurface temperatures below 5 m are generally stable throughout the year. The thermocouples in this study are at depths from 15.2 to 122 m below ground surface. The shallowest thermocouple was three times the depth at which the outside ambient air can affect the ground temperature.

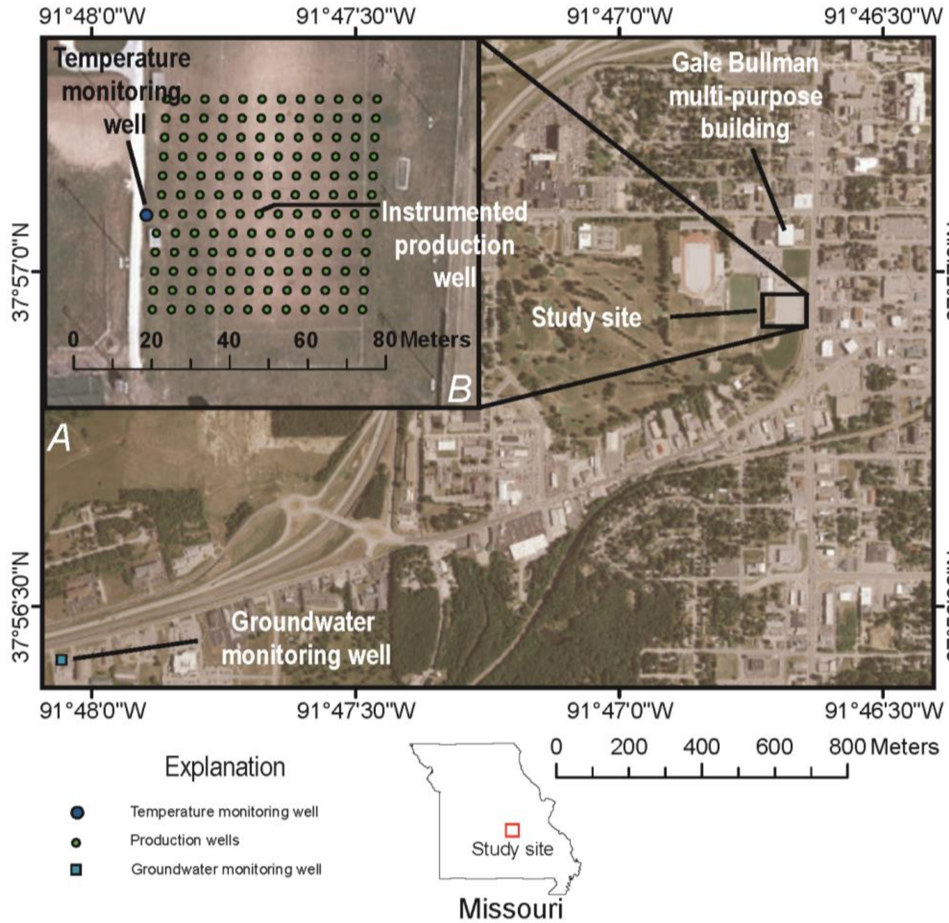

Figure 1. Location of study site in Rolla, Missouri, 2015-16 (A) and plan view of the borehole heat exchanger (B; Smith et al., in review).

2. METHODS

2.1 SITE DESCRIPTION

The BHE is part of a much larger system on the Missouri University of Science and Technology (S&T) campus. The overall S&T GCHP system consists of 789 wells serving three primary plants and satellite system. The satellite system serves the Gale Bullman Multipurpose Building which uses the 144 well BHE in this study for heat flux to and from the subsurface and is exclusively in the Ozark Aquifer which is the most important source of water for most towns, water districts, and private wells in the Salem Plateau (Miller and Vandike, 1997). The aquifer is characterized by high production wells where private wells can produce more than enough water for residential use and large diameter wells can produce upwards of 1,100 to over 3,800 liters per minute

(MDNR, 2017). The wells extend through 122 meters (m) of soil and rock which is classified into 5 units based the well's boring log and historical logs (003409, 009515, 011737, and 014397) of nearby wells.

The surface, from zero to 6 m, generally consists of residuum which is a product of the weathering of carbonate rocks. The Jefferson City Dolomite generally consists of dolomite and is located from 6 to 52 m below the surface. The Roubidoux Formation is located at 52 to 88 m below the surface and generally consists of sandstone and dolomite. The Upper Gasconade Dolomite is located from 88 m to 110 m below the surface and is predominately dolomite. The Lower Gasconade Dolomite is at the bottom of the BHE from 110 m to greater than 122 m (total depth of wells) below the surface and generally ranges from dolomite to cherty dolomite.

The Roubidoux Formation and the Lower Gascondade Dolomite tend to be higher producers of water compared to the other formations surrounding the BHE (Miller and Vandike, 1997). The Roubidoux Formation consists of interbedded sandstone, cherty dolomite, and sandy dolomite. It also has very high secondary porosity as a result of historic fracturing from the dolomitization process and structural movement (Miller and Vandike, 1997). Secondary porosity may be an important factor in the changes in efficiency of BHEs (Smith et al., in review, Chiasson et al., 2000). The Lower Gasconade Dolomite consists of cherty dolomite and is considered a relatively high producer of water in the Rolla area (Vandike, 1992). Conversely, the Jefferson City Dolomite and the Upper Gasconade Dolomite have relatively low-permeability when compared to the Roubidoux Formation and the Lower Gascondade Dolomite. Vandike (1992) described the Lower Gascondade Dolomite as a leaky confining unit due to its low porosity.

2.2 INSTRUMENTATION

The individual BHE wells were constructed using a single 3.175 centimeter diameter Geoguard high-density polyethylene (HDPE) u-tube. The u-tube was grouted in to each 15 centimeter borehole for water circulation. Thermocouples where installed on the center production well u-tube at 15.2-m intervals from 15.2 m below the surface to 122 m below the surface which is also the total depth of the borehole. Two Omega™ SA2C-T thermocouples were attached to the BHE u-tube with one on the inflow side and one on the outflow side. The 6 thermocouples from 15.2 to 45.7 m were installed in the interval of the u-tube within the Jefferson City Dolomite. The 4 thermocouples at 61.0 and 76.2 m were installed in the interval of the u-tube within the Roubidoux Formation. The 4 thermocouples at 91.4 and 106.7 m were installed in the interval of the u-tube within the Upper Gasconade Dolomite. The last 2 thermocouples were installed in the interval of the u-tube within the Lower Gasconade Dolomite. Two Campbell Scientific CR 10 dataloggers were used to record the thermocouple temperature measurements. Measurements were taken at 15 minute intervals to coincide with data recorded within the Gale Bullman multipurpose building which included flowrate, and water temperatures entering the building from the BHE and leaving the building to the BHE.

The temperature of the water leaving the nearby Gale Bullman Multipurpose Building and entering from the nearby BHE was collected by the Physical Facilities Department as a way to monitor the system's performance. Temperature measurements and the flowrate of the BHE circulation fluid was recorded every 15 minutes. This data was used in conjunction with direct temperature measurements of the area at the interface of the u-tube and the surrounding rock formations in order to characterize how the differing formations interact with the BHE.

2.3 DATA ANALYSIS

Temperature measured by the thermocouples at different depths of the borehole was analyzed using boxplots, scatter plots and summary statistics. Instantaneous heat flux ($\dot{q}$) through the wall of the u-tube was calculated for each discrete temperature measurement using Equation 1 (Incropera and DeWitt, 2002).

$$\dot{q} = -k\,\frac{T_1 - T_2}{L} \tag{1}$$

A minimum thermal conductivity (k) value of 0.4 Watts per meter Kelvin was used for the polyethylene u-tube (Ineos, 2017). T_1 was the temperature of the circulation fluid at the specific depth of the thermocouple. This value was calculated by determining the rate of temperature change from the water entering the BHE to the temperature when it leaves the BHE. This was calculated by dividing the difference in the temperature of the water entering the BHE and leaving the BHE by the total length of the u-tube (144 m). The temperature (T_2) directly on the outside of the u-tube is measured by the thermocouples.

Heat flux at each depth was analyzed using scatter plots and summary statistics. Further statistical analysis of the heat flux grouped by individual depths was conducted using the Kruskal-Wallis One-way Analysis of Variance (Kruskal and Wallis, 1952) to characterize the overall differences in the groups and the Dwass-Steel-Chritchlow-Fligner Test (Dwass, 1960; Steel, 1960; Critchlow and Fligner, 1991) was used for pairwise comparisons of the individual groups. This was used to determine if the heat flux at different depths were statistically different.

3. RESULTS

3.1 PRODUCTION WELL TEMPERATURE VARIATION

Overall, temperatures measured by thermocouples within the production well generally remained cooler in the lower thermocouple locations with surrounding geologic material composed predominately of dolomite (47.5, 61.0, 91.4, 106.7, and 122.0 meters (m) below ground surface) while energy was rejected into the subsurface (warming of the aquifer) as shown in Figure 2 and Table 1. The median temperature recorded at these locations ranged from 19.5 to 20.4 degrees Celsius (°C). Conversely, temperatures measured by thermocouples within the production well nearest to the surface (15.2 and 30.5 m) and the thermocouple location at 76.2 m generally remained warmer than the other intervals. The median temperature recorded at these locations ranged from 21.8 to 22.0 degrees Celsius (°C) as shown in Table 1.

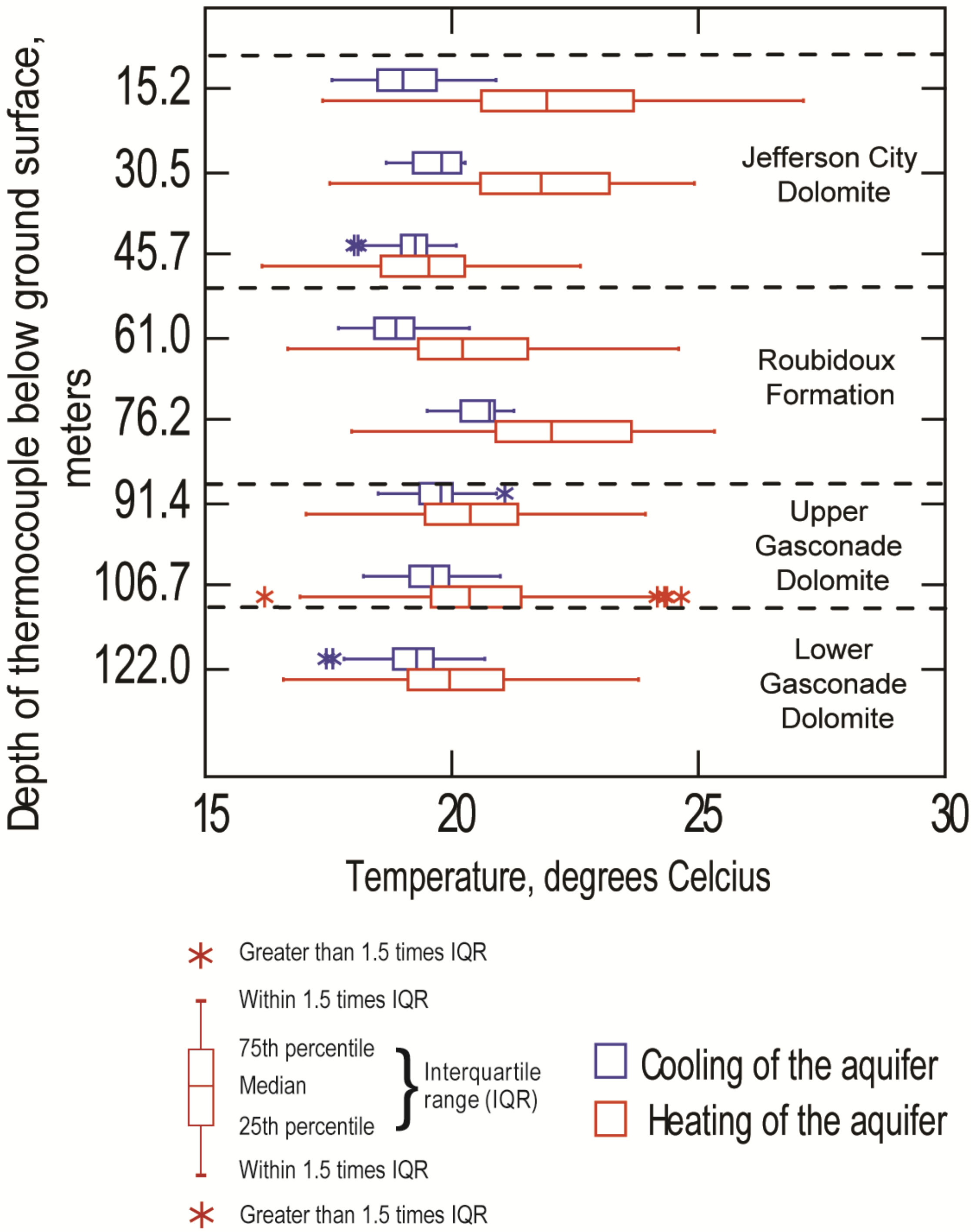

Figure 2. Boxplots showing the temperature variations as measured by thermocouples at the interface of the u-tube and grout in the single production well of the borehole heat exchanger.

Table 1. Summary statistics of discrete temperature measurements recorded at multiple depths within the production well.

			Heating of the aquifer					Cooling of the aquifer					Overall		
Depth (m)	Formation	General Description	Cases	Median (°C)	Arithmetic Mean (°C)	25th percentile (°C)	75th percentile (°C)	Cases	Median (°C)	Arithmetic Mean (°C)	25th percentile (°C)	75th percentile (°C)	Difference in Medians (Δ°C)	Median (°C)	Range (Δ°C)
15.2	Jefferson City Dolomite	Dolomite, 95%; chert, 5%	1,092	21.9	22.2	20.6	23.7	132	19.0	19.1	18.5	19.7	2.9	20.2	11.0
30.5	Jefferson City Dolomite	Dolomite, 95%; chert, 5%	564	21.8	21.8	20.6	23.2	12	19.8	19.7	19.2	20.2	2.0	21.1	8.4
45.7	Jefferson City Dolomite	Dolomite, 75%; chert, 20%; sandstone, 5%	1,092	19.5	19.5	18.6	20.3	132	19.3	19.2	19.0	19.5	0.3	19.3	7.3
61.0	Roubidoux Formation	Sandstone, 60%; dolomite, 40%	1,092	20.2	20.5	19.3	21.5	132	18.9	18.9	18.4	19.2	1.4	19.6	9.0
76.2	Roubidoux Formation	Dolomite, 60%; chert, 30%; sandstone, 10%	564	22.0	22.2	20.9	23.6	12	20.8	20.6	20.2	20.9	1.3	21.6	8.3
91.4	Upper Gasconade Dolomite	Dolomite, 90%; chert, 10%	1,035	20.4	20.4	19.5	21.3	121	19.8	19.7	19.3	20.0	0.6	19.8	7.8
106.7	Upper Gasconade Dolomite	Chert, 60%; dolomite, 30%	1,078	20.4	20.6	19.6	21.4	132	19.6	19.6	19.1	19.9	0.7	20.3	9.5
122.0	Lower Gasconade Dolomite	Dolomite, 90%; chert, 10%	1,092	20.0	20.1	19.1	21.0	132	19.3	19.2	18.8	19.6	0.7	19.8	8.1

Overall, the greatest difference in median temperatures during heat rejection, heating of the aquifer, and heat withdrawal, cooling of the aquifer, tended to be greatest at the two locations nearest to the surface followed by the two locations in the Roubidoux Formation. Temperatures tended to remain fairly consistent at all depths during cooling. Median temperatures were less than 20 °C with the exception of the location at 76.2 m (20.8 °C) which also tended to be warmer during hotter days when heat was rejected to the aquifer as shown in Table 1. The cooling periods were modest and typical of predawn in late spring and early summer for the area and are not representative of the aquifers response to substantial heat withdrawal in the cold winter months. The modest cooling does, however, show how the aquifer's and individual lithological unit's respond to directional changes of heat flux to or from the borehole heat exchanger (BHE). The largest difference in median temperatures during heat rejection and heat withdrawal tended to be greatest at the two locations nearest to the surface (15.2 and 30.5 m) with differences in the median temperatures of 2.9 and 2.0 Δ°C followed by the two locations (61.0 and 76.2 m) in the Roubidoux Formation with differences in the median temperatures of 1.4 and 1.3 Δ°C. The differences in the median temperatures for the remaining locations in the Jefferson City Dolomite (47.5 m), Upper Gasconade Dolomite (91.4 and 106.7 m), and the Lower Gasconade (122.0 m) ranges from 0.3 to 0.7 Δ°C as shown in and Table 1.

Overall temperatures at the thermocouple locations increased steadily overtime through April to mid-May when the rate of change began to increase throughout the mid May and all of June as shown in Figure 3. The greatest overall increase in temperature was at a depth of 15.2 m which was the location nearest to the surface as shown in Figure 3. The mean smoother line indicated that the location warmed to just less than 25 °C as shown in Figure 3B. This location is in the Jefferson City Dolomite just below the interface of residuum and bedrock (Jefferson City Dolomite). The least overall increase in temperature was at a depth of 45.7 m as shown in Figure 3. The mean smoother line indicated that the location warmed to just greater than 20 °C as shown in Figure 3B. This was the deepest location in the Jefferson City Dolomite. The other locations warmed to within the 22 to 23 °C range.

3.2 HEAT FLUX

Overall, the heat flux from the circulation fluid through the u-tube wall to the grout increased steadily during the study from April to June as shown in Figure 4. The location with the greatest heat flux was correspondingly the location that remained coolest during the study. This was the location at a depth of 45.7 m in the Jefferson City Dolomite (Figures 3 and 4). The relatively cooler temperatures at this depth likely allowed for greater heat flux. However, the least heat flux was correspondingly the location that remained warmest during the study. This was the location nearest to the surface at a depth of 15.2 m also in the Jefferson City Dolomite (Figures 3 and 4). This location, which is likely indicative of a larger interval, tended resist heat flux compared to the other locations in the production well when the system attempted to reject heat at a greater rate during the hotter summer months.

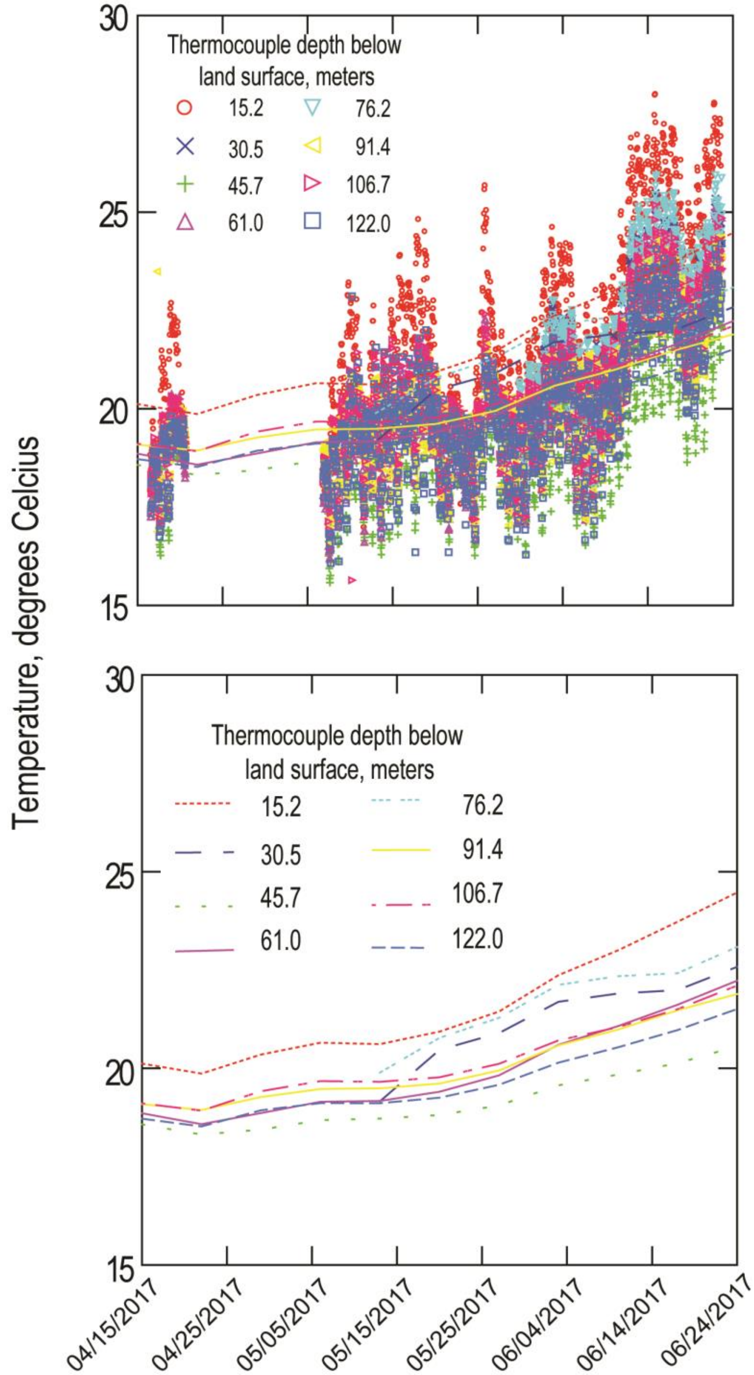

Figure 3. Temperature measured by thermocouples at the interface of the u-tube and grout in a single production well of the borehole heat exchanger from April 17, 2017 to June 23, 2017.

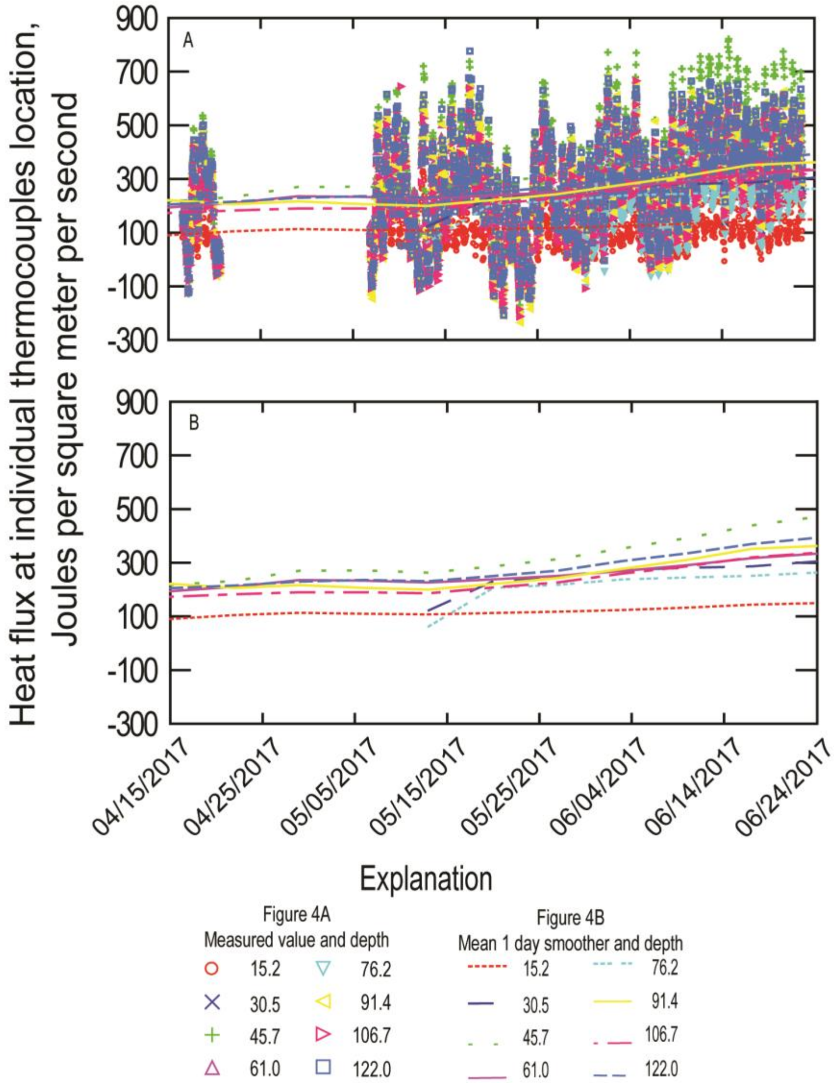

Figure 4. Heat flux calculated through the u-tube wall between the circulation fluid and the grout in the single production well of the borehole heat exchanger at different depths from April 17, 2017 to June 23, 2017.

Median and mean heat flux also displayed a similar trend. Overall the location with the greatest median [345 joules per square meter per second (J/s/m^2)] and mean (339 J/s/m^2) heat flux was at a depth of 45.7 m in the Jefferson City Dolomite (Table 2). It was followed by depth of 122 m which is at the deepest point in the production well in the Lower Gasconade Dolomite and had a median heat flux of 310 J/s/m^2 and a mean heat flux of 292 J/s/m^2 as shown in Table 2. The locations with the lowest median and mean heat flux were the location nearest to the surface at a depth of 15.2 m in the Jefferson City Dolomite (median heat flux of 103 J/s/m^2 and mean heat flux of 122 J/s/m^2) and the location at 76.2 m in the Roubidoux Formation (median heat flux of 244 J/s/m^2 and mean heat flux of 245 J/s/m^2) and shown in Table 2.

Table 2. Summary statistics for heat flux calculated from thermocouple temperature measurements, temperature of circulation fluid flowing in and out of the borehole heat exchanger, and the thermal conductivity of the polyethylene u-tube. All values are in units of joules per second per square meter.

Depth (m)	Formation	General Description[1]	Minimum	Maximum	Range	Median	Arithmetic Mean
15.2	Jefferson City Dolomite	Dolomite, 95%; Chert, 5%	-78	403	481	103	122
30.5	Jefferson City Dolomite	Dolomite, 95%; Chert, 5%	-22	558	581	281	281
45.7	Jefferson City Dolomite	Dolomite, 75%; chert, 20%; sandstone, 5%	-196	821	1,018	345	339
61.0	Roubidoux Formation	Sandstone, 60%; dolomite, 40%	-125	617	742	272	265
76.2	Roubidoux Formation	Dolomite, 60%; chert, 30%; sandstone, 10%	-104	548	652	244	245
91.4	Upper Gasconade Dolomite	Dolomite, 90%; chert, 10%	-427	684	1,111	282	268
106.7	Upper Gasconade Dolomite	Chert, 60%; Dolomite, 30%	-506	666	1,172	255	245
122.0	Lower Gasconade Dolomite	Dolomite, 90%; chert, 10%	-208	776	984	310	292

[1] General description determined from Missouri well log 009515 and by cuttings collected from the production well used in this study.

The temperatures ranges recorded at each depth tend to show correlation to the median heat flux. The late spring and early summer ambient air temperatures required the system to apply cyclic heating to the aquifer as shown in Figure 2. The location nearest to the surface (15.2 m) had the largest temperature range of 11.0 Δ°C (Table 1) but had the smallest median heat flux of 103 J/s/m^2 (Table 2). The location with the smallest temperature range of 7.3 Δ°C (Table 1) had the largest median heat flux of 345 J/s/m^2. The best fit line of temperature ranges recorded at each depth and their corresponding median heat flux had a correlation coefficient of 0.83 as shown in Figure 5. This indicates the heat flux tends to increase as the range of measured temperatures decrease during cyclic heating of the aquifer. This is likely due to higher thermally conductive layers being able to better dissipate heat. Conversely, lower thermally conductive layers have less of an ability to regulate temperature and can easily build up heat rejected by BHE leading to greater increases in temperature. The greater increase in temperature in lower thermally conductive layers may also cool more quickly when the BHE begins circulating cooler water for the purpose of heating during a cooler night because of the large temperature difference. In future studies, the temperature range at each location adjacent to the u-tube may be an effective indicator of the performance of different geologic units for heating and cooling using ground coupled heat pump (GCHP) systems.

3.3 STATISTICAL ANALYSIS

The Kruskal-Wallis One-way Analysis of Variance was used to determine if the heat flux values calculated from temperature measurements recorded at each depth and the corresponding temperatures of the water entering and leaving the BHE were statistically different overall. The results of the test indicated that the groups are statistically different overall with a p-value of 0.00 as shown in Table 3.

Further analysis using the Dwass-Steel-Chritchlow-Fligner Test for pairwise comparison was used to determine if the groups of discrete heat flux values were statistically different from other individual groups. Overall, most tests resulted in p-values less than 0.05 indicating that there was a significant difference between the groups with few exceptions. Only three tests had p-values greater than 0.05 (Tests 11, 21, and 23; Table 3) indicating that the null hypothesis, that the mean ranks of the groups are the same, could not be rejected. The pairwise comparison for all heat flux groups at the 2 locations in the production well with greatest median heat flux (45.7 and 122.0 m) and the location with the lowest heat flux (15.2 m) all had p-values less than 0.05 indicating that these groups were statistically different than the other groups of heat flux as shown in Table 3.

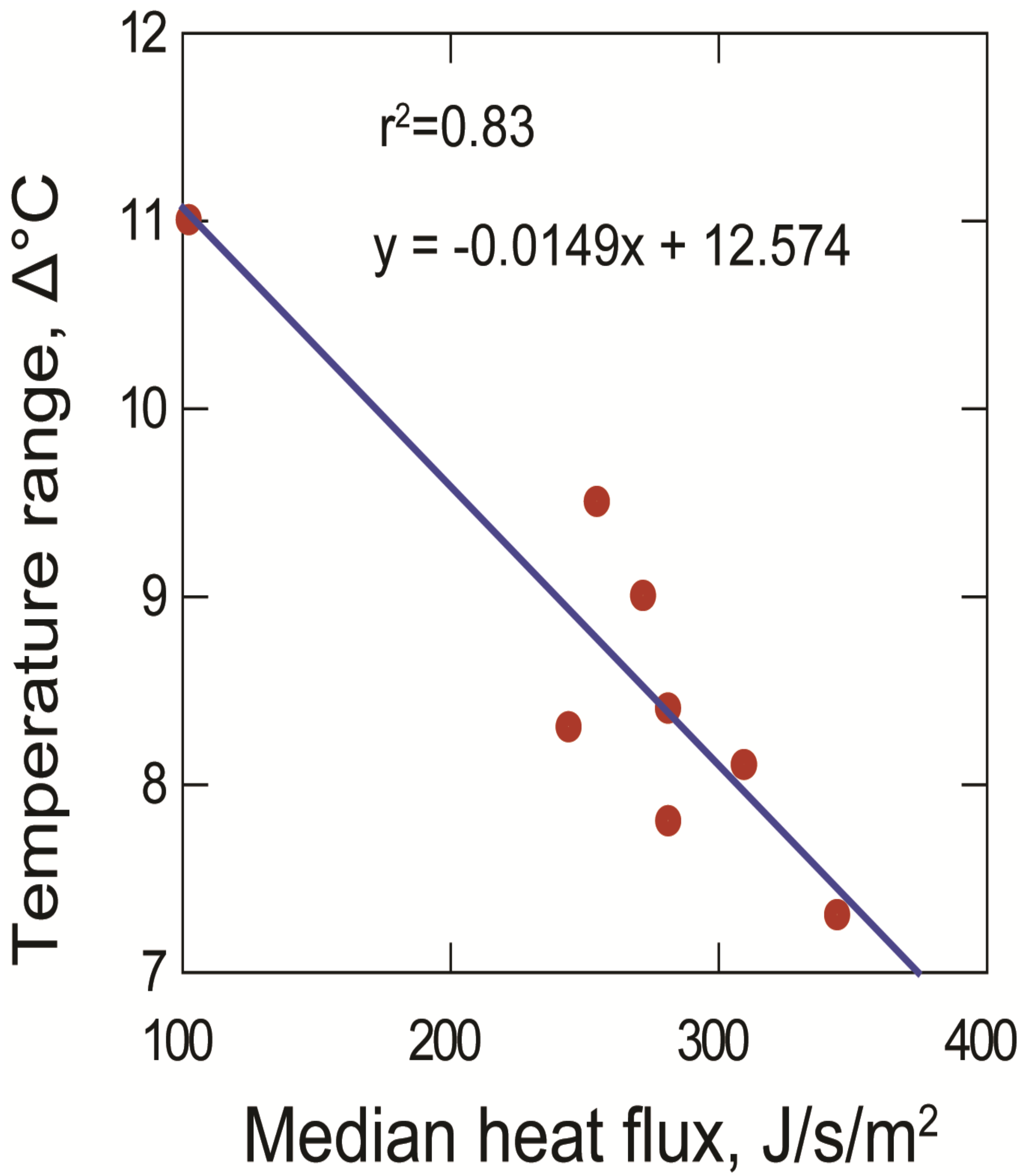

Figure 5. Scatterplot showing the correlation of the range of temperatures at each depth and the median calculated heat flux.

Table 3. Results of the Kruskal-Wallis One-way Analysis of Variance and Dwass-Steel-Chritchlow-Fligner Test.

Kruskal-Wallis One-way Analysis of Variance				
Test	Group(i)	Group(j)	Statistic	p-Value
KW	All groups		1,052.3	0.00

Dwass-Steel-Chritchlow-Fligner Test				
Test	Group(i)	Group(j)	Statistic	p-Value
1	15.2	30.5	25.5	0.00
2	15.2	45.7	34.1	0.00
3	15.2	61.0	28.6	0.00
4	15.2	76.2	19.0	0.00
5	15.2	91.4	14.2	0.00
6	15.2	106.7	25.0	0.00
7	15.2	122.0	29.2	0.00
8	30.5	45.7	20.0	0.00
9	30.5	61.0	5.7	0.00
10	30.5	76.2	-6.1	0.00
11	30.5	91.4	-2.9	0.47
12	30.5	106.7	4.4	0.04
13	30.5	122.0	11.0	0.00
14	45.7	61.0	-16.0	0.00
15	45.7	76.2	-23.5	0.00
16	45.7	91.4	-21.4	0.00
17	45.7	106.7	-16.6	0.00
18	45.7	122.0	-10.6	0.00
19	61.0	76.2	-11.0	0.00
20	61.0	91.4	-7.1	0.00
21	61.0	106.7	-0.7	1.00
22	61.0	122.0	6.2	0.00
23	76.2	91.4	1.3	0.99
24	76.2	106.7	9.2	0.00
25	76.2	122.0	15.3	0.00
26	91.4	106.7	6.2	0.00
27	91.4	122.0	12.3	0.00
28	106.7	122.0	6.7	0.00

Gray shading indicates that the p-value was greater than 0.05 and that the null hypotheses (the groups come from equal distributions) cannot be rejected therefore the groups are not statistically different.

3.4 LITHOLOGY AND HYDROLOGICAL EFFECTS

The two locations nearest to the surface (15.2 and 30.5 m) were in the Jefferson City Dolomite and were both composed of predominately dolomite and some chert as shown in Table 1. Despite the similar compositions the lower location at 30.5 m tended to perform much better for heat flux (median heat flux of 103 J/s/m^2 at 15.2 m and 281 J/s/m^2 at 30.5 m; Table 2) indicating that it may be in a location that is more saturated with groundwater. Smith et al. (in review) reported that the saturation of the aquifer at this site greatly affected the performance of the BHE. A decrease in saturation due to drought would likely be observed as a decrease in the median heat flux at the depth of 30.5 m.

Overall, the depths below 15.2 m with 75 percent or greater dolomite tended to have greater performance by having the highest median heat flux as shown in Table 2. The 4 highest median heat fluxes were at depths of 30.5, 45.7, 91.4, and 122.0 m with heat flux ranging from 281 to 345. Conversely, the locations below 15.2 m with the 2 lowest median heat fluxes had 30 percent or greater chert composition. This lithology effect is likely because dolomite tends to have greater thermal conductivity than both chert and sandstone. While there is some overlap in the ranges of values for dolomite and sandstone, chert generally has the lowest thermal conductivity. Majorwicz and Jessop (1981) reported thermal conductivity values of 5.0±0.6 Watts per meter Kelvin (W/mK) for dolomite, 4.2±1.4 W/mK for sandstone and 4.2±1.3 W/mK for chert while observing heat flow patterns in the Western Canadian Sedimentary Basin. Beach et al. (1987) reported thermal conductivity values 3.1±1.4 W/mK for dolomite, 3.1±1.3 W/mK for sandstone, and 1.4±0.5 W/mK for chert while observing heat flow in the western Canadian prairies basin in Alberta, Canada. Reiter and Jessop (1985) reported thermal conductivity values of 4.7±0.8 W/mK for dolomite, 3.7±1.2 W/mK for sandstone, and 1.4±0.5 W/mK for chert in rocks from the Canadian Atlantic Shelf.

4. CONCLUSIONS

This study showed that monitoring temperature directly adjacent to u-tubes of deep borehole heat exchangers (BHE) with multiple individual sensors at different depths can help characterize the ability of different lithological units to conduct heat efficiently. Temperature measurements at the interface of the u-tubes and grout overtime located at different depths to represent the different lithological units will help stakeholders in the design and planning process of for these large ground coupled heat pump (GCHP) systems.

The study was conducted during an aquifer heating cycle of late spring and early summer as heat was rejected into the subsurface from the BHE. This created a cyclic heating effect with heat being rejected from the BHE in the warmer afternoons and considerably less heat or even cooling in the early mornings. The thermocouples recorded a range of temperatures during this time. Overall, the median heat flux at each depth tended to decrease with increasing range of temperatures recorded by the thermocouples. This indicated that higher thermally conductive layers remain cooler during heating as heat is quickly conducted into the formation. Lower thermally conductive layers cannot easily conduct heat causing it to build up and resulting in an increase in the measured temperature range during cyclic heating.

The depth (15.2 m) nearest to the surface where saturation was likely lowest compared to the deeper water bearing units had the lowest median heat flux and largest temperature range overall, suggesting large effects due to low saturation. Locations where saturation was greater, below 15.2 m, with 75 percent or greater dolomite composition tended to have greater performance with the highest median heat flux. Conversely, the locations below 15.2 m with the 2 lowest median heat flux had 30 percent or greater chert composition suggesting significant lithological effects on the BHE performance.

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SECTION

3. CONCLUSIONS

There have been numerous studies on small-scale ground coupled heat pump (GCHP) systems. However, large-scale GCHP systems are relatively recent constructs with many systems coming on line in the past 10 years and more are in the design and planning or construction phase. The ability of GCHP systems to store energy in the subsurface during the summer and extracting the energy during the winter is one of the most efficient indoor heating and cooling methods. The larger the system is at a specific site generally means greater magnitudes of heat transfer to or from the subsurface allowing for heating and cooling of numerous buildings. This has made large-scale GCHP systems popular among institutions such as colleges. The reported benefits from these large systems, such as reduced use of fossil fuel consumption, CO_2 emissions, and water consumption, should encourage further growth of these systems.

Currently, the thermal response test is the industry standard for calculating the effective thermal conductivity of the geologic material surrounding borehole heat exchangers (BHE). This method is limited as it is conducted once over a 48 hour period and results in an effective thermal conductivity of combined geologic materials, current saturation of the aquifer, and current groundwater flow conditions at one point in time. It does not reflect long-term changes in groundwater conditions due to seasonal changes, drought, or climate change nor does it investigate the influence of varied lithology.

New methods for characterizing large-scale GCHP system's interactions with the subsurface are urgently needed. The new methods will be required to provide valuable information on long-term changes in both the saturation of the aquifer and groundwater flow and the effects of lithology on the BHE. These can greatly affect the overall performance of large-scale GCHP systems. A larger system generally means greater heat transfer to or from the subsurface which means small changes of groundwater saturation or flow can result in larger magnitude of changes in heat transfer rate. Larger changes could even result in a decrease in the anticipated heat transfer rate. This may further result in expensive modifications to the original design. Characterization of the lithology will also assist in the system design by identifying zones more conducive of heat transfer.

A greater understanding of how large-scale GCHP systems interact with the subsurface has many important benefits. It will result in systems that perform more efficiently over a longer period of time and expensive modifications will be reduced due to unforeseen changes in system performance. Above all, it will encourage greater stewardship of aquifer systems.

4. RECCOMMENDATIONS FOR FUTURE RESEARCH

4.1 LONG-TERM STUDIES

Newly planned large-scale ground coupled heat pump (GCHP) systems will provide opportunity to further understand a GCHP system's borehole heat exchanger's (BHE) interaction with the local hydrology and geology. This will benefit both the system in the study and future systems nearby or at sites with similar hydrology and geology. Hydraulic conductivity and permeability can vary greatly among different types of soil and lithology. This can have a dramatic impact on GCHP systems when changes in groundwater saturation or flow are present. The methods outlined in these papers provide a foundation for which to base these future studies.

With that said, it is important to tailor these investigations to the study site. Thermocouples installed on or near production well u-tubes should be strategically placed to best represent specific rock units or interfaces of the saturated and unsaturated zones. This is also true for temperature monitoring wells. It is more important to install thermocouples on the incoming water side of the u-tube rather than the outgoing water side. This incoming water side will see the greatest temperature changes because as the water changes direction at the bottom of the borehole and returns to the surface, it has already gained or lost a large percentage of energy. This will provide greater insight into the BHE's interaction with different formations or zones of differing saturation.

A strong quality assurance and quality control plan should be implemented. One disadvantage of grouting thermocouples into the borehole is that they become permanent with no method to verify the accuracy. A method to ensure accuracy is by comparing replicate measurements by thermocouples at the same location in a borehole. The thermocouples can be placed side by side so that they are essentially measuring the same location. Large differences in the temperature measurements of the thermocouples should remain the same. One or both thermocouples may start to become inaccurate over time if their temperatures begin to drift apart over time. A thermocouple may be failing if it is experiencing unusual temperature swings relative to an opposite co-located thermocouple. A comparison of the datalogger and thermocouple measurements to a calibrated thermometer before installation will ensure a properly working system before installation.

4.2 EVALUATION OF THERMAL RESPONSE TEST OVER TIME

The thermal response test (TRT) is the industry standard for estimation of the thermal properties of the geologic material surrounding large-scale GCHP system's BHE (Florea et al., 2016, Gehlin, 2002; Sanner et al., 2005). The TRT can only capture the effective thermal conductivity of the combined geologic material at that particular point in time. It does not have the ability to reflect changes in aquifer saturation or groundwater flow over time. It is possible to overcome this limitation by conducting multiple TRTs during known periods of low or high aquifer saturation and low and high groundwater flow. This will produce a range of effective thermal conductivities that would be expected throughout a year of operation despite seasonal changes. This needs to be completed in order to determine how different the results of the TRTs will be from each other and how that would affect the design of these large-scale GCHP systems. This research will assess how effective a single TRT is and if it needs modification to be an effective tool in the design of large-scale GCHP systems.

The TRT should be completed during a wide range of groundwater conditions which means that the site will have to meet certain criteria for a successful study.

1. The rock and soil around the borehole for the TRT should have relatively high hydraulic conductivity such as sands, gravels, and fractured rock. These tend to be more affected by changes in groundwater conditions (Chiasson et al., 2000).
2. Multiple wells should be on site to monitor current water levels and to determine the magnitude of groundwater flow.
3. There should be several years of historical water levels to help identify periods of low and high saturation of the aquifer as shown in Figure 4.1.

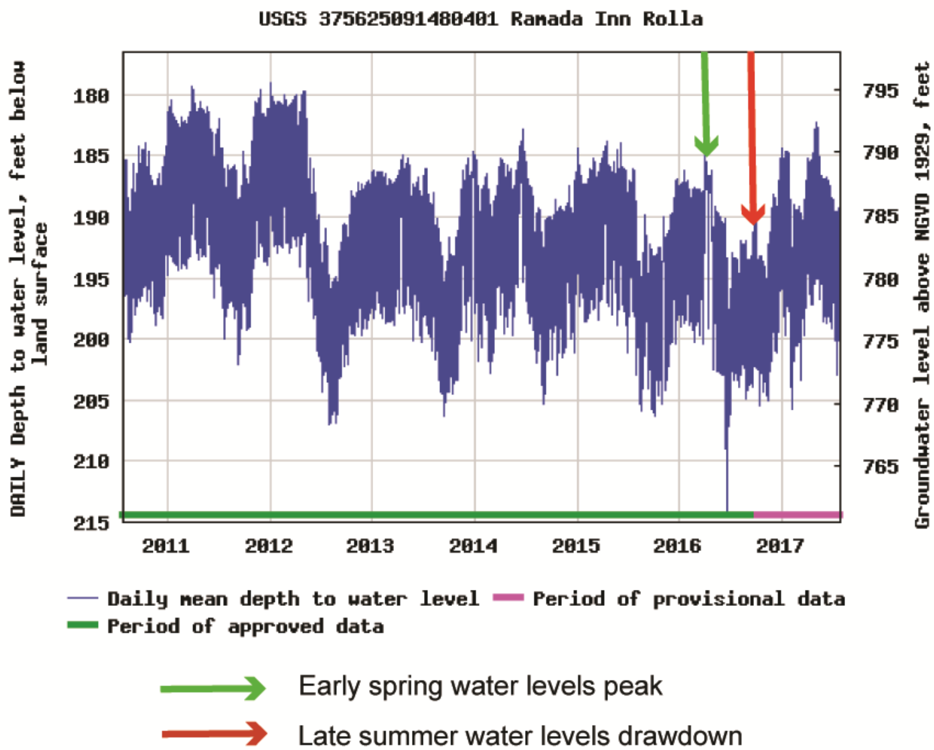

Figure 4.1 Long term hydrograph of water levels at the Missouri Department of Natural Resources Groundwater Monitoring Network Well USGS 375625091480401 Ramada Inn Rolla.

4. A TRT should be conducted multiple times during the course of a year. A TRT should be conducted during but not limited to:
    a. Groundwater level peaks (typically in early spring)
    b. Groundwater level troughs (typically in late summer)
    c. High groundwater flow and low groundwater flow (may coincide with groundwater level peaks and troughs)
    d. After periods of intense rainfall [may be important for shallow alluvial unconfined aquifers (Mohamed et al., 2015)]

The study should not be limited to single TRTs for each event. It would be beneficial to conduct a TRT during a range of conditions to find which parameter typically correlates with the thermal conductivity determined by the TRT. This along with the range of thermal conductivity values will help identify the conditions that tend to have the greatest effect on the performance of the BHE. The thermal conductivity values should be compared to design standards which are an important metric for the effects of changes in groundwater conditions. Significant differences in the design due to varying thermal conductivity values, e.g. number of boreholes or number of auxiliary cooling towers, would be a strong indicator that a single TRT could cause the system to be poorly designed too high or too low heating and cooling capacity.

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