



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 a borehole heat exchanger (BHE) within a large scale closed-loop geothermal system to changes in groundwater flow, as a result of periodic pumping of a large municipal well. The BHE studied consists of 144 geoechange boreholes drilled to a depth of 122 m into karstic bedrock of the Ozark Aquifer. Estimated groundwater flows rates range from 15 to 1.1×10^{-3} m/year were measured, and the effectiveness of the BHE during pumping was calculated to understand the effects of groundwater flow on the system. Changes in the BHE effectiveness under varying flow rates were compared to estimates from previous study estimates with changes in aquifer saturation. Overall, the variations in aquifer saturation tended to have the greatest influence on the effectiveness of the BHE.

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 pumps (GCHP) have been shown to be efficient heating and cooling systems for large- and small-scale buildings. These systems are designed to 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 < 15 m (Piscaglia et al., 2016; Bense and Kooi, 2004). This is attributed to the high thermal inertia of soil and rock (Florides and Kalogirou, 2007) but can be impacted by land use changes (Colombani et al., 2016).

GCHP systems are becoming more common due to their efficiency. From 1994 to 2004, the use of GCHP increased by 10% per year. The systems were installed in 30 countries, and the fastest growth occurred in the US and Europe (Lund et al., 2004). From 2010 to 2014, the use of GCHP increased by 7.7% per year worldwide (Lund and Boyd, 2016). Large district-scale systems have also become more common. For example, the one of largest systems built in the US is at Ball State University (BSU) in Muncie, Indiana (Florea et al., 2017). The GCHP system consists of 3600 boreholes drilled to depths between 122 and 152 m and is used to heat and cool 47 buildings (511,000 m²). This allowed the University to decommission its fossil-fuel boilers which reduced

CO₂ emissions by 77,000 metric tons and resulted in annual savings of \$2 million (BSU, 2016). Stockton College in southern New Jersey completed a large GCHP system in 1994 (Zapeczka, 1989; Taylor et al., 1997). Other institutions across the US 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 system is designed to replace an existing heating and cooling system, which over the last 70 years provided steam to campus by burning coal and woodchips. The system consists of 789 closed-loop boreholes between 122 and 134 m deep. The borefields serve three primary campus GCHP plants and one satellite plant at the 42,178 m² Gale Bullman Multi-Purpose Building. Each plant contains heat recovery chillers (500 tons capacity), supplementary cooling towers, and gas-fired boilers. The boilers are used to assist with heating and cooling of buildings during periods when extreme temperatures occur. The new GCHP system has allowed S&T to reduce its annual energy consumption by 57%, CO₂ emissions by 25,000 metric tons/year, and water usage by 70.9 million liters/year per year (S&T, 2016).

This paper describes the impact of the local groundwater flow on BHEs in 144 boreholes that serve the Gale Bullman Multi-Purpose Building. The borefield covers an area of 2860 m² and differs from other

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systems (e.g., Stockton College) in that the boreholes are constructed in 122 m of interstratified karstic dolomite and sandstone, which form the Ozark Aquifer. The boreholes extend through 6 m surficial of residuum, 46 m of dolomite (Jefferson City Formation), 37 m of dolomite and sandstone (Rubidoux Formation), and 34 m of dolomite and cherty dolomite (Gasconade Formation) (MDNR, 2017). It is important to note that the S&T geology is similar to BSU where limestone and shale predominantly underlie the borefields (e.g., Well log #421719: IDNR, 2009). The site in this study is also centered within a large area identified as karst (Epstein et al., 2002).

There have been multiple studies that have considered the effects of groundwater on small GCHP systems (e.g., Mohamed et al., 2015; Chiasson et al., 2000; Lee and Lam, 2007, 2008; Fan et al., 2007). Groundwater can affect the BHE performance in two general ways.

1. The presence of groundwater can affect the thermal properties of the surrounding geologic materials, whether it is bedrock, sediment, 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, 2008; Fan et al., 2007).

To study these performance issues, Mohamed et al. (2015) designed a bench-scale GCHP system to characterize the effects of both vertical groundwater flow and fluctuations in water levels. To monitor thermal transport in the system, 26 type-t thermocouples monitored the temperature of the heat exchanger, the sand surrounding the BHE, and the inlet and outlet temperature of fluid in the heat exchanger. The fluid was moved through the heat exchanger using a parasitic pump, and tested with varying water levels conditions to simulate different precipitation and saturation scenarios. Mohamed et al. (2015) concluded that both the water 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 than when dry. Heat recovery was four times greater when the water level was above the heat exchanger 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 BHE performance. 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 by incorporating groundwater flow into GCHP models which are used in the design of GCHP and more specifically, sizing the BHE. 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 by examining the Peclet number of the flow using a finite-element numerical groundwater flow and heat transfer model.

Despite a growing body of research on smaller GCHP systems and simulated models, most district-scale GCHP systems are relatively recent constructions with little attention given to site hydrogeology (Florea et al., 2017; Smith et al., in review). The design of BHEs rely on the thermal response test (TRTs) which is generally conducted once and does not take into account changes in levels of groundwater flow, which may not change significantly during the course of a 48 h 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. Local aquifer saturation was estimated based on water level in a nearby real-time groundwater monitoring well. 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. 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 borehole BHE shown in Fig. 1 which is a subsystem of the GCHP system for the building. The dolomite and sandstone bedrock are productive aquifers that form part of the Ozark Aquifer, which is a major source of groundwater in parts of Missouri, Kansas, Oklahoma, and Arkansas (Imes and Emmett, 1994; Vandike, 1992; Miller and Vandike, 1997). The city of Rolla has 18 municipal production wells in the aquifer, screened in the Gasconade Formation. Overall, groundwater withdrawals in Rolla and the surrounding county were approximately 12.3 million liters/day in 2010 (USGS, 2014), which has trended upward since 1945 (Vandike, 1992) as demand by the university and the city increases. A monitoring well used to measure subsurface temperatures was drilled 6 m west of the borefield and centered within the 144 borehole (Fig. 1). The well is used to monitor the ambient temperature of the groundwater.

A large municipal well field is located in the study approximately 335 m south of the BHE (Fig. 1). The pumping capacity of the well is approximately 2135 l per minute (564 gallons per minute; PDWS Reports, 2016). The well was drilled to a depth of 350 m and has a static water level of approximately 75 m below ground surface (bgs). The well is cased to 85 m, 3 m into the Gasconade Formation (MDNR, 1947), and the BHE also extends through 34 m of the formation (Fig. 2.). The BHE and well are both open at the bottom to the Gasconade Formation.

2.2. Instrumentation

Eight Omega™ SA2C-T (type-t) thermocouples were installed at 15 m intervals starting at 15 m bgs on 3.8 cm diameter high-density polyethylene (HDPE) pipe that extended 122 m bgs to the bottom of the borehole. 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 15–122 m interval between the data logger and individual thermocouples. Two Campbell Scientific CR10X data loggers recorded thermocouple readings between August and December 2015, and two Campbell Scientific CR10 data loggers were active between (January and July 2016). The data loggers were housed in a weather-proof box within an underground concrete enclosure. Temperature data was recorded every 60 min from September to December 2015, and every 30 min from January to July 2016 (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 energy and water systems, and the data provided to the study, including water temperature entering the BHE, temperature of water leaving the BHE, and the flow rate. These parameters were measured every 15 min.

2.3. Data analysis

The effectiveness of the BHE was the focus of the study, and how it changes as the groundwater flow rate varies due to the intermittent operation of the nearby municipal well. The effectiveness was calculated using Eq. (1), from Incropera and DeWitt (2002): the ratio of the

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