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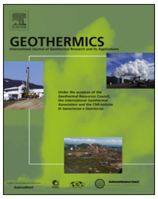

The effect of seasonal groundwater saturation on the effectiveness of large scale borehole heat exchangers in a karstic aquifer

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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 bedrock. The BHE consisted of 144 production wells drilled to a depth of 122 m into karstic bedrock. Water 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. Our study assembled evidence that a single borehole thermal response tests in karstic environments may not capture the seasonal changes in the saturation of the surrounding bedrock. Complete 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.

1. Introduction

The Earth's climate has warmed by 0.6 °C over the past 100 years (Walther et al., 2002) and concern has greatly increased 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 or geoexchange, are beginning to play a more prominent role in the US to decrease the amount of CO_2 released into the atmosphere. These systems use borehole heat exchangers (BHE) to inject or extract heat into or from the subsurface for cooling or heating purposes, respectively. The usage of these systems has increased 10 percent annually in about 30 countries from 1994 to 2004 (Lund et al., 2004). GCHP use has increased by 7.7% per year worldwide from 2010 to 2014 (Lund and Boyd, 2016). 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 deep subsurface maintains a stable temperature throughout the year. This allows GCHP systems to be so effective. The effects of seasonal and diurnal temperature changes are diminished with depth, and ground temperature measurements have shown that they are relatively stable below 7–15 m (Florides et al., 2011; Bense and Kooi, 2004) due to the high thermal inertia of soil and rock (Florides and Kalogirou, 2007).

Due to the relatively stable ground temperatures for deep BHEs, the influence of ground temperature may play a minor role in the effectiveness of BHEs, however changes in groundwater saturation may play an important role. Groundwater conditions can greatly affect the effectiveness of GCHPs and the associated BHEs by changing the thermal properties of the surrounding geologic formations (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 constructed within the laboratory. High groundwater levels in poorly graded sand enhanced the heat recovery of the ground heat exchanger. To account for these on GCHP, Molina-Giraldo et al., 2011, Diao et al., 2004, and Fan et al., 2007 incorporated groundwater advection into their models. Chiasson et al. (2000) used a numerical model to show how groundwater flow significantly enhances heat transfer in sands, gravels, and fractured bedrock having a high hydraulic conductivity. Sandstone, and karstic dolostone and limestone, have primary intergranular and secondary fracture permeability, and the degree of saturation of these bedrock can greatly influence the thermal properties

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(Busby et al., 2009).

Piscaglia et al. (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 2-story commercial building with a total area of 1152 m^2. The BHE consisted of 6 closed-loop wells drilled into marly-limestone reservoir rock to a 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 al. (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.

It is not well understood how 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 has begun to be adopted in the United States. For example, Ball State University's (BSU) GCHP system went online in the spring of 2012, initially reducing its reliance on four aging coal-fired boilers, and has since been considered the largest in the nation. In 2014, The Missouri University of Science and Technology (S&T) completed a GCHP system comparable in size to BSU's 2012 system in an effort to reduce heating and cooling costs and water use. It was one of the largest systems in the country at the time of construction. The GCHP system consists of 789 BHEs of 122 m and 134 m length, which serves 3 primary campus GCHP plants and one satellite plant (Gale Bullman Building). The BHE in this study serves the 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.

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 and therefore will be relevant for future large-scale BHE projects such as at BSU and S&T. 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.

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; Spreng and Proctor, 1999). The BHE used in this study is services the Gale Bullman Multi-Purpose Building satellite system. The Gale-Bullman building (42,178 m^2) BHE borefield consists of 144 closed-loop wells. Their locations are shown in Fig. 1, each well being drilled to a depth of 123 m bgs. The geologic units in which the wells are completed include residuum (6 m thick) and three karstic units: dolostone of the Jefferson City Formation (46 m thick), dolostone and sandstone of the Rubidoux Formation (37 m thick), and dolostone and cherty dolostone of the Gasconade Formation (34 m thick). All of the formations are prolific aquifer units and form part of the Ozark Aquifer which is a major source of groundwater for parts of Missouri, Kansas, Oklahoma, and Arkansas (Imes and Emmett, 1994; Miller and Vandike, 1997; Vandike, 1992).

A 3.2-cm diameter Geoguard high-density polyethylene (HDPE) u-tube, was installed in each of the 15.2-cm diameter boreholes in the geothermal system. The u-tubes are grouted in using a mixture of graphite, quartz sand, and thermal grout, which is specifically designed to maximize the thermal efficiency of BHEs.

The circulating fluid (pure water) in the BHE system generally has a flow rate between 58.2–68.4 m^3/min during normal weather conditions, but can increase to as high as 149.4 m^3/min during hot or cold weather. The initial thermal response test (TRT) for this borefield was conducted from June 26–28, 2011 (48 h) in order to determine the thermal properties of the surrounding rock. The TRT was conducted by a private company on a test well outside of the borefield (12 m) and determined an effective thermal conductivity of 2.6 BTU/hr·ft·°F. The TRT was not incorporated into the study with the exception of how it may be related to changes in ground water levels.

2.2. Instrumentation

The temperature monitoring well is centrally within the borefield, located 6 m from the center of the west side of the borefield (Fig. 1). Eight Omega™ SA2C-T thermocouples were installed at 15 m intervals along the 122 m, 3.8-cm diameter HDPE pipe, which extended from the land surface to the bottom of the borehole. A similar well configuration with Omega k-type thermocouples is described by Florides et al. (2011). The SA2C-T are self-adhesive t-type thermocouples specifically designed for curved surfaces, such as u-tubes. T-type 16-gauge extension wire was used to minimize the resistance used over relatively long distances from the bottom of the well to the ground 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 store the measurements. Temperature data was recorded at 60 min (min) intervals from September–December 2015, and 30 min intervals from January– July 2016.

The temperature was recorded at the following depths: 15 m, 30 m, 46 m, 61 m, 76 m, 91 m, 107 m, and 122 m bgs. The thermocouple nearest to the surface in this study was at 15 m bgs and ground temperatures tended to remain stable throughout the year at this depth. The temperature of the circulating water was recorded by the HVAC system. Measurements were taken both before the water was returned into the subsurface and as the water re-entered the building from the subsurface. The pumping rate was recorded every 15 min.

Water level data collected from a groundwater monitoring well in the Missouri Groundwater Observation Network, located 1.3 miles from the BHE borefield (Fig. 1). The well is managed by the Missouri Department of Natural Resources in cooperation with the U.S. Geological Survey (USGS, 2016). Water levels are recorded every 30 min 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. Total precipitation is also recorded at the well at 30 min intervals using a tipping bucket rain gauge.

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 Eq. (1) (from Incropera and DeWitt, 2002).

Effectiveness of BHE

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

The energy gained or rejected from the ground loop (h) was calculated in Eq. (2) (from Incropera and DeWitt, 2002) where T_i is the temperature of the water entering the BHE, T_o is the temperature of the