Subsurface Thermal Anomalies From Low Temperature Geothermal Systems

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ABSTRACT
Geothermal systems are generally regarded as a “green” energy source, however, recent studies have highlighted that the migration of thermal anomalies associated with these subsurface systems can result in adverse impacts to both environmental receptors and adjacent property owners. In this study, environmental implications of geothermal systems will be evaluated by using collected and existing temperature data to create numerical models capable of predicting the extent of thermal changes caused by the long-term operation of a geothermal system. Observations and model results will be used to assist in the creation of guidelines to develop geothermal resources in a sustainable manner.

RÉSUMÉ
Des systèmes géothermiques sont généralement considérés car une source d'énergie « verte », cependant, des études récentes ont accentué que la migration des anomalies thermiques liées à ces systèmes à fleur de terre peut avoir comme conséquence des impacts défavorables aux récepteurs environnementaux et aux propriétaires adjacents. Dans cette étude, des implications environnementales des systèmes géothermiques seront évaluées par des données de rassembler et existantes d'utilisation de la température pour créer les modèles numériques capables de prévoir l'ampleur des changements de courant ascendant provoqués par l'opération à long terme d'un système géothermique. Des observations et les résultats modèles seront employés pour aider à la création des directives pour développer les ressources géothermiques d'une façon soutenable.

1 INTRODUCTION

Low-temperature geothermal energy, also often referred to as Earth energy or Geoexchange, has become increasingly popular in Canada over the past several years. Figures reported by Freeston (1996) and Lund and Freeston (2001) and Lund et al. (2005) indicate use in TJ/yr has increased by a factor of approximately 25 in the ten year period between 1995 and 2005 (refer to Figure 1). There are currently over 30000 known instances of geothermal energy use in Canada, with this number increasing rapidly. Despite this popularity, our understanding of the impacts of these systems on the subsurface, both in terms of environmental impacts and thermal sustainability has not improved significantly, primarily because of a lack of monitoring, system post-audits and a general lack of concern on the part of many installers. In this study, we address some of these larger scale impacts, including the potential impacts of open-loop systems on source water protection plans and the relationship between groundwater and closed-loop heat pumps.

Groundwater flow is known to have significant effect on subsurface thermal energy developments. Previous research has dealt with the importance of regional groundwater flow on aquifer thermal energy storage (Gringarten and Sauty, 1975; Ferguson and Woodbury, 2006; Banks, 2009) but similar consideration has not been given to systems that do not extract or inject water into the subsurface directly. Possible contamination associated with drilling and fluids circulated in boreholes and heat exchangers has also been addressed in many studies and is the subject of a great deal of regulations, such as CSA C448. Other environmental impacts, such as geochemical reactions and impacts on surface water have also been noted as issues by other researchers (Goldschedier and Bechtel, 2009; Ferguson, 2009). However, there is somewhat of a dearth of studies on the impact of groundwater flow on the design and performance of these systems. Some studies (e.g Chiasson et al., 2000; Fan et al., 2007) have noted that groundwater flow can create an increase in the apparent thermal conductivity in thermal response tests. There have also been some efforts to derive analytical solutions to the differential equation describing advective-conductive heat transport for the case of a line-source of heat in a porous medium with regional groundwater flow. However, these studies have not explicitly examined the effect of advection on the distribution of subsurface temperatures as it related to hydrogeologic parameters. In this study, the effect of advection on the distribution of subsurface temperatures will be examined over a range of Darcy velocities and implications for underground thermal energy system (UTES) design will be illustrated with numerical models. Implications to site investigations will be discussed and a method for using rock and soil types as a first order tool will be presented.

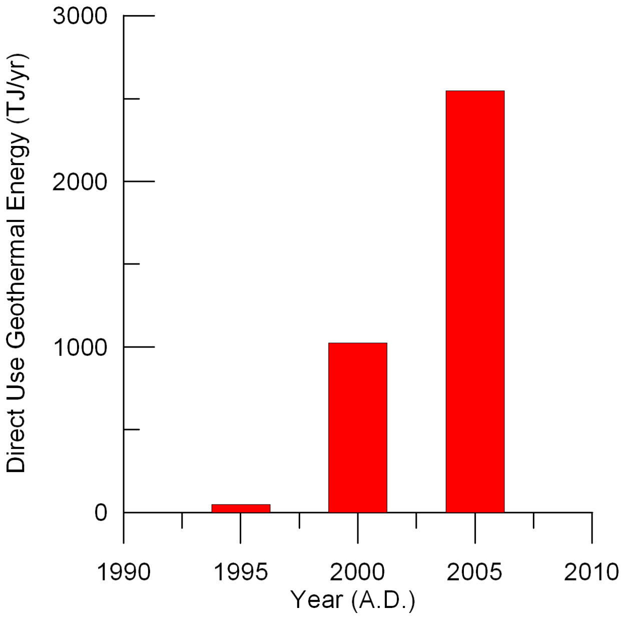

Figure 1: Direct use of geothermal energy in Canada (from Freeston (1996), Lund and Freeston (2001) and Lund et al. (2005)).

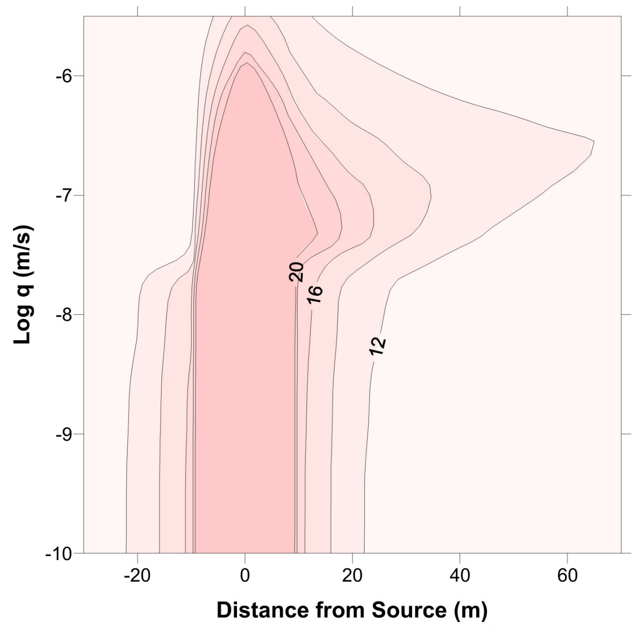

Figure 2: Temperature anomalies for different Darcy fluxes after 10 years of operation for a small closed-loop system.

2 GENERIC MODELS OF CLOSED LOOP SYSTEMS

2.1 Numerical Modelling – Effect of Advective Heat Transport on Closed Loop Systems

An examination of the impact of groundwater flow on a heat pump after 10 years of operation was examined to provide an idea of the importance of conduction and advection in various environments. A line source of 5 KW was placed at the centre of the model to a depth of 50 m to represent a small geothermal system. At the east and west sides of the model, hydraulic gradients were used and permeability was varied in different model runs to create different Darcy fluxes across the line source. Permeability and groundwater flow were uniform across the entire model domain. Groundwater fluxes of zero were prescribed for the north and south sides of the model. A temperature of 10°C was used as the initial temperature throughout the model domain and this value was also used as a fixed temperature boundary condition on all lateral temperature boundaries.

The results of these models are shown in Figure 2 and indicate a transition from conduction-dominated environments to environments where advection is an important consideration at a Darcy flux of approximately 10^{-8} m/s. The maximum potential for a noticeable thermal plume (>1 Kelvin) occurs at approximately 10^{-7} m/s. At greater Darcy flux values, plumes will be more extensive but the temperatures will be lower. This result occurs because there is not enough heat coming from the closed-loop system to heat the amount of water crossing the line source.

2.2 Case Study

As part of this study, the hydrogeology and heat flow of an area surrounding a closed-loop system installed at a community centre in Halifax Regional Municipality (HRM) was examined. The location of the case study site is provided in Figure 3. The system, which includes a borehole field of 12 boreholes approximately 152 metres deep, was installed in 2008 as part of building construction to meet the building's heating and cooling requirements. The investigation carried out at the site prior to system installation relied on a previous geotechnical report and utilized thermal properties obtained from another geothermal energy project in HRM approximately 20 km away. Soon after the system began operating, the system had to be shutdown due a leak in the system that resulted in the loss of several hundred litres of propylene glycol to the subsurface. That incident is not the focus of this case study but as part of the investigation to assess the environmental impact; three piezometers were installed down gradient of the system. Drilling in the area of the geothermal borehole field encountered approximately 2 m of fill underlain by approximately 2 m of till and fractured slate bedrock.

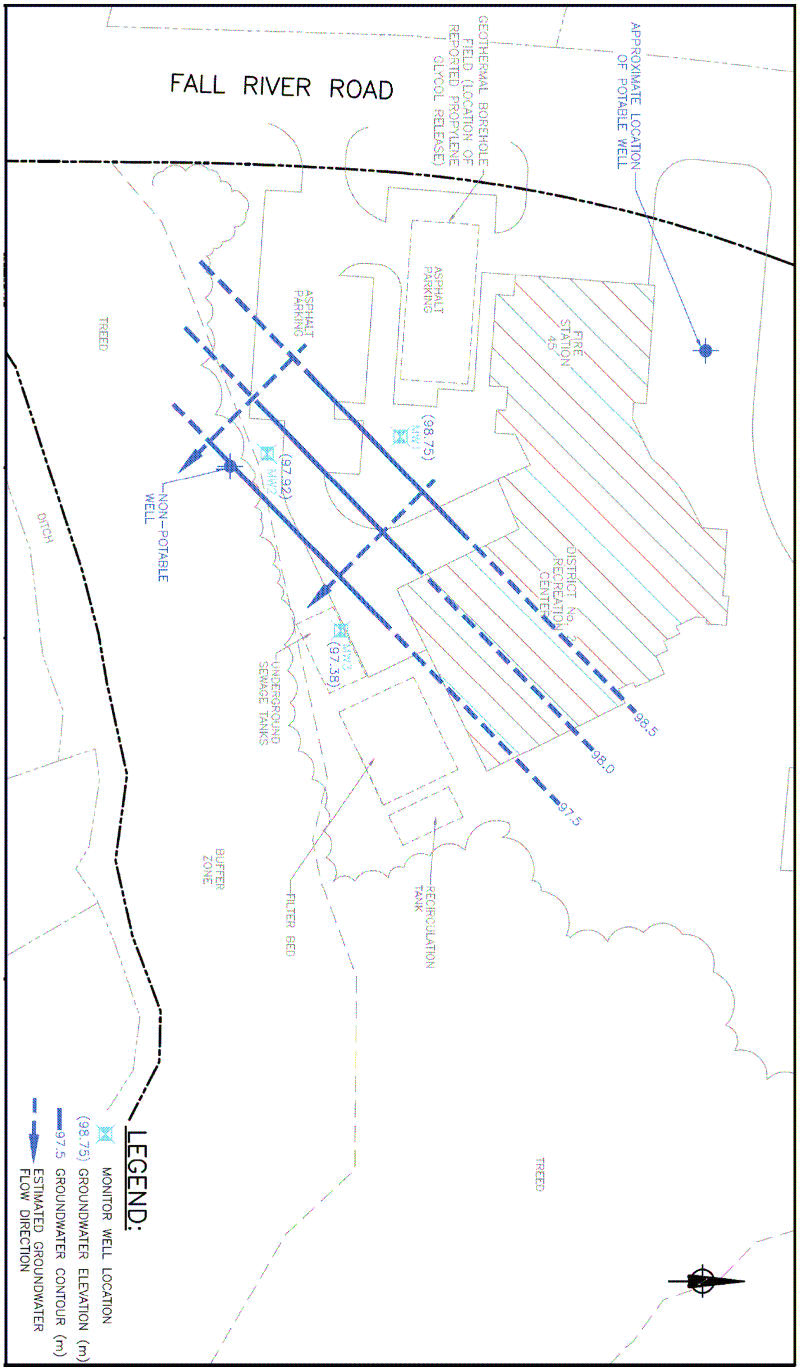

Figure 3: Location of site of case study.

Temperature profiles have been recorded at this site on April 1, 2009 and April 30, 2009 (Figures 4, 5 and 6). The average shallow groundwater temperatures in HRM for the month of April typically range from 6 to 7 °C (D. MacFarlane, pers. comm., 2009). Therefore, the temperatures themselves are no reason for alarm but the rate of change and the position of maximum change do provide some insight into the nature of heat flow at this location. Temperatures in all three piezometers experienced the greatest change at the bottom of the profile, suggesting that changes in temperature are being forced from a depth at least as deep as the piezometers, likely associated with the closed-loop heat pump, rather than being driven by temperatures changes at the ground surface. The changes and the distances and timing of these are of interest because we can derive some information about the rate of groundwater flow. There is currently not enough information available to create and calibrate a detailed predictive model but we can use the preliminary data to constrain the relative importance of conduction and advection. The conductive signal should not reach anywhere near this far after a months of operation for this system. Considering the time of operation and distances from the borehole field at this property suggest linear groundwater velocities on the order of 10^{-5} m/s, which would correspond to a Darcy flux of 10^{-6} m/s if a porosity of 10% is assumed. A marginally lower estimate is arrived at by examining the hydraulic gradient at the site in combination with an estimated hydraulic conductivity of 10^{-5} m/s for the fractured slate in the area (D. MacFarlane, pers. comm., 2009). The magnitude of temperature change is unlikely if the temperature anomaly is this great over the entire depth of the closed-loop at this site, suggesting that flow of both heat and groundwater is focused in the upper reaches of the fractured slate bedrock, which was encountered at an average depth of approximately 4 m below grade, and perhaps in other more permeable zones at depth. Exploratory drilling for domestic water well at this site supports this idea. Multiple wells were drilled and none produced a sufficient amount of water to provide a supply for this building, indicating that while the permeability of the upper portion of the bedrock is high, the transmissivity of the unit is relatively low.

If groundwater flow had been considered prior to system installation, the importance of advection would have been obvious. This may have had implications to the design of the system in terms of orientation and the amount of piping required. Environmental implications, particularly to nearby Lake Thomas may have also received some consideration as well. The effect of geothermal projects on surface water habitats has received some attention (e.g. McCray, 1997) but the impacts are not well understood at this point although a substantial body of literature (see Sophochocleous, 2002 and references therein) suggests that groundwater plays an important role in regulating the temperature of surface water bodies. The specific details of the thermal response are not currently well constrained. Further monitoring of temperature responses at these piezometers, in combination with further field investigations to characterize the heterogeneity in hydraulic and thermal properties will be necessary to gain a more complete understanding of heat transport at this site. The importance of heterogeneity also indicates that far more complex modeling will be necessary to predict the future extent of the thermal plume emanating from this system.

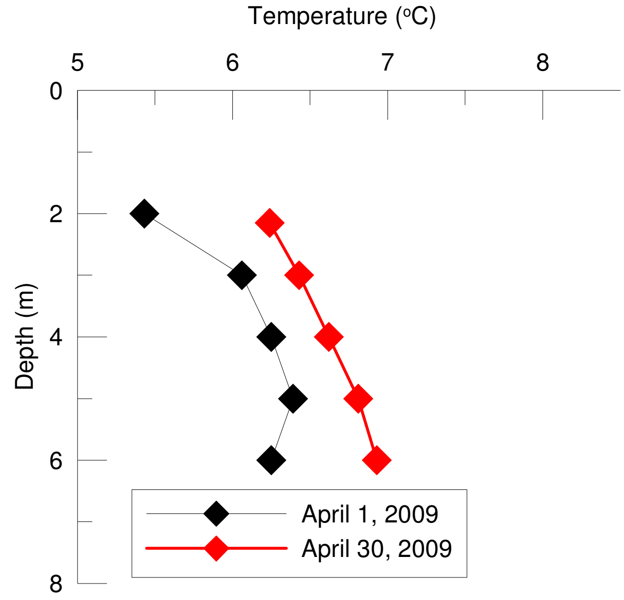

Figure 4: Temperature profiles for MW1 at the Fall River Site

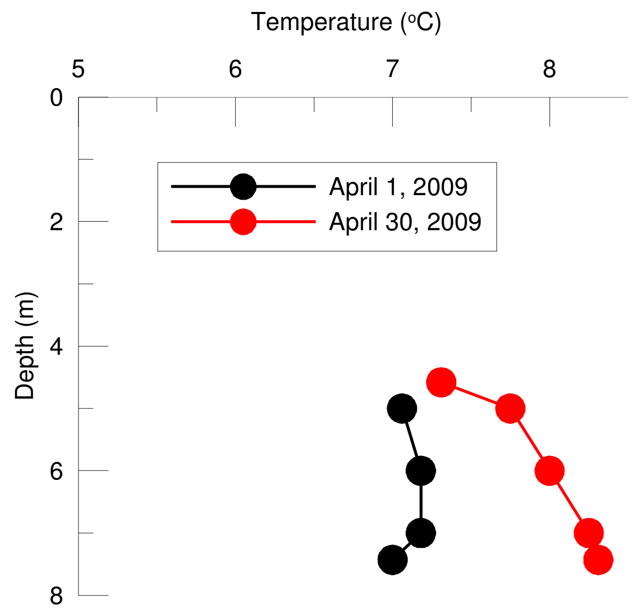

Figure 5: Temperature profiles for MW2 at the Fall River Site.

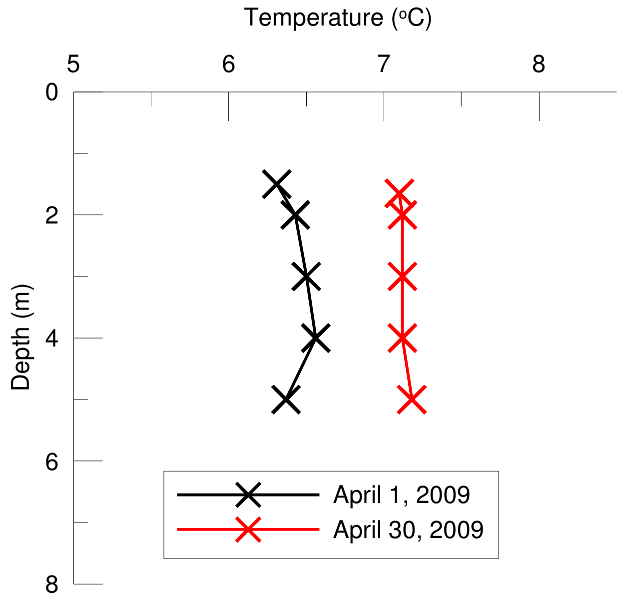

Figure 6: Temperature profiles for MW3 at the Fall River Site.

Further research will focus on additional sites in Nova Scotia. The lack of transferability of design parameters from one site to another indicates that a variety of sites will need to be examined to understand the behaviour of these systems over the long-term. Current plans include investigations of a large closed-loop system in Port Hawkesbury, NS, an open-loop system in the Annapolis Valley, several smaller closed-loop systems in HRM and project currently in the design will not cover the complete range of geophysical conditions in Nova Scotia, it is hoped that they will be useful in developing guidelines for site investigations and to support the development of a regulatory framework.

3 CONCLUSIONS

The current level effort put into site investigations prior to installation of ground-source heat pumps is likely inadequate in many cases. A lack of understanding of heat flow in the subsurface can result in system overdesign, extension of thermal footprints beyond property boundaries and heat transport towards environmental receptors. While these issues may not be of importance in all systems, current regulations do not necessarily provide the framework to assess these problems and further research is required to allow for optimal use of geothermal resources.

4 ACKNOWLEDGEMENTS

This research was supported by a grant from the Atlantic Innovation Fund.

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