THE IMPORTANCE OF HYDROGEOLOGICAL INFORMATION IN GEOTHERMAL ENERGY DEVELOPMENTS
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ABSTRACT
Geothermal energy is becoming increasingly popular due rising energy prices and concerns about greenhouse gas emissions. Many of these projects involve either extraction of groundwater or storage of hot or cold water in the subsurface but in many cases little attention has been given to the hydrogeology of the area to be developed. Hydrogeological investigations should be conducted in geothermal energy developments to increase the efficiency of such systems and allow for sustainability. Heterogeneous conditions will have a significant impact on thermal transport rates and the distribution of heat in the subsurface. Understanding these variations in permeability will enable more certainty in injection and production schedules and increased efficiency. Hydrogeological information will become increasingly valuable as the number of geothermal energy users increase, which will raise the potential for hydraulic and thermal interference between individual systems. Hydrogeologists and groundwater engineers must become more involved in the planning of geothermal energy developments to ensure that this resource is used to its full potential.

1. INTRODUCTION
The use of groundwater in thermal applications is currently receiving a great deal of interest due high energy costs and a demand for alternative energy sources. Development of groundwater resources for thermal purposes is being promoted by various agencies and in several jurisdictions in Canada there are currently financial incentives for choosing to use geothermal energy rather than traditional sources such as natural gas, oil and electricity. However, in many cases these promotions have been put in place without adequately considering the environmental and hydrogeological aspects of development. In theory this does not appear to be a large problem because many of these systems employ injection-withdrawal well pairs (doublets) and mathematical analysis of such systems in homogeneous environments suggests that the only hydrogeological parameter required for design is porosity (Gringarten and Sauty, 1975). However, a study of several systems in Winnipeg, Manitoba (Ferguson and Woodbury, 2006) suggested in heterogeneous environments, the behaviour of these systems is much less predictable. In the current study, the effect of heterogeneity is examined using a series of numerical simulations using randomly generated permeability fields.

2. SIMULATION OF ADVECTIVE HEAT TRANSPORT IN HETEROGENEOUS ENVIRONMENTS
2.1 Generation of Permeability Fields
Permeability fields were generated using HYDRO_GEN (Bellin and Rubin, 1996), a computer code for generating spatially correlated random space functions. In the current study, the option for exponential covariance was selected. Two cases were selected to examine different levels of heterogeneity. In the first case, the geostatistics of the Borden aquifer (Table 1; Woodbury and Sudicky, 1991) were employed. The Borden aquifer was selected to provide a case that was nearly homogeneous. The second case utilized the geostatistics of the Carbonate Rock aquifer in southern Manitoba (Table 1; Kennedy and Woodbury, 2002). This case represents a more heterogeneous aquifer and is perhaps more important in a geothermal sense as it is one of the most highly exploited aquifers in Canada for thermal purposes. Thirty realizations of the permeability field (m²) for each aquifer on a two-dimensional 10 m by 10 m grid covering an area 1260 m by 1260 m were created for use in subsequent models.
Table 1: Geostatistics used to generate the permeability fields in this study. Note that the Borden data is given as hydraulic conductivity and Carbonate Rock data is given in the natural log of transmissivity. The randomly generated fields were divided by the average thickness of the aquifer to provide hydraulic conductivity values.

<table>
<thead>
<tr>
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<th>Borden Carbonate Rock</th>
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<tbody>
<tr>
<td>Mean Ln K</td>
<td>-4.62 -7.2</td>
</tr>
<tr>
<td>Variance</td>
<td>0.261 1.6</td>
</tr>
<tr>
<td>Integral Scale</td>
<td>5.14 2.7</td>
</tr>
</tbody>
</table>

2.2 Numerical Models

Advective-conductive heat transport models were created using METRA, which is a submodule of MULTIFLO (Painter and Seth, 2001). In these models, fixed hydraulic head boundary conditions were imposed on all lateral boundaries of the model domain. In the centre of the domain, a production well and injection well were placed 100 m apart and both were assigned pumping rates of 3.8 L/s (60 USGPM). The aquifer was initially assigned a uniform temperature of 20°C and injected water was assigned a temperature of 10°C. A temperature of 10°C was also assigned as fixed boundary conditions for all edges of the model domain. Although injection temperature would likely change following temperature changes at the production well, such effects were not considered in this exercise. A uniform porosity of 5% was used for all simulations in this study along with a thermal conductivity of 2.5 W/(m K) and thermal diffusivity of $10^{-6}$ m$^2$/s.

3. RESULTS

Production well temperatures for the 30 realizations of advective-conductive heat transport for the simulations using the Borden geostatistics showed very little variability over 25 years of development (Figure 1). At one year, there was a greater variance in temperature than after 25 years (Figure 3; Table 2).

Figure 1: Realization of ln k field for Borden geostatistics. Scale in m.

Figure 2: Realization of ln k field for Carbonate Rock Aquifer geostatistics. Scale in m.

Table 2: Production well temperature results for the ensembles of stochastic simulations conducted in this study.

<table>
<thead>
<tr>
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<th>Borden Carbonate Rock</th>
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<tbody>
<tr>
<td></td>
<td>1 year 25 years 1 year 25 years</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>17.616 11.780 17.629 11.791</td>
</tr>
<tr>
<td>Mean</td>
<td>17.562 11.809 17.625 11.752</td>
</tr>
<tr>
<td>Median</td>
<td>17.589 11.833 17.634 11.730</td>
</tr>
<tr>
<td>Variance</td>
<td>0.078 0.013 0.024 0.129</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.009 -0.132 -0.577 0.064</td>
</tr>
</tbody>
</table>
Production well temperatures for the 30 realizations using the Carbonate Rock aquifer geostatistics showed more variability overall than those for the Borden aquifer (Figure 4; Table 2). However, the Carbonate Rock aquifer simulations exhibit greater variance at 25 years than at 1 year (Figures 4; Table 2). It should also be noted that 36 permeability fields were actually used in this analysis but six of these realizations resulted in severe drawdown leading to model failure.

The introduction of heterogeneity into the numerical simulations had a pronounced affect on the certainty on the spatial distribution of the thermal anomaly. The distribution of regions with the highest variance changed with time, appearing in the immediate vicinity of the pumping well at early times and moving perpendicular to the axis of the doublet and towards the production well with time (Figure 5). This movement appears to be consistent with the movement of the advective front along various flow lines and subsequent equalization of temperatures by diffusion.

Figure 4: Production well temperatures for 30 stochastic realizations based on Carbonate Rock Aquifer geostatistics, dashed line is homogeneous case with mean hydraulic conductivity
4. DISCUSSION AND CONCLUSIONS

Spatial variations in permeability have a noticeable effect on the behaviour of heat transport in geothermal developments. These effects appear to be relatively insignificant in more homogeneous environments if the wells are situated at a distance greater than the integral scale. This is apparent in the Borden results where the variance on the ensemble of realizations decreases with time. However, heat transport in aquifers characterized by large integral scale, such as the Carbonate Rock Aquifer, will be less predictable when wells are spaced at distances much smaller than the integral scale.

While it is generally accepted that spreading of solutes in porous media are linked to spatial variability in permeability (Dagan, 1994), there has been little effort to examine how these variations affect heat transport. The heterogeneities affected the overall thermal response of the aquifer in this study but there is no clear trend that suggests this decreases the overall temperature at the production well or changes the timing of temperature increases. This insensitivity agrees with the results of Tiedeman and Hsieh (2004), who found that macrodispersion was of lesser importance in forced-gradient tests.

Collection of a greater amount of information on the spatial distribution of permeability will provide a more certain understanding of heat transport during thermal development. Pump tests conducted at the production and injection wells are often the primary source of hydrogeological information in the site investigation conducted prior to these developments, often without additional observation wells. However, the simulations conducted in this study suggest that these may be insufficient to predict long-term behaviour. This shortcoming will be particularly problematic if it is necessary to predict temperatures in areas of the aquifer that are at some distance from the pumping wells. In such cases, a variety of techniques might be of use in predicting heat transport within the aquifer. These include tracer testing using either solutes or heat, pump hydraulic tomography (Yeh and Liu, 2000), slug testing and geophysical testing to help characterize heterogeneity within the aquifer (e.g. seismic, electromagnetic and other techniques that measure responses correlated with porosity or permeability). However, it may not be possible to gauge long-term behaviour of hydrogeological systems from relatively short tests (Bredehoeft, 2002), suggesting that long-term monitoring might be necessary in larger developments. Regardless of the approach, it is apparent that hydrogeological science has an important contribution to the development of geothermal energy.

5. ACKNOWLEDGEMENTS

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References


