
Observed thermal pollution and post-development simulations of low-temperature geothermal systems in Winnipeg, Canada

Grant Ferguson · Allan D. Woodbury

Abstract Two issues arise in the long-term use of groundwater for thermal purposes: (1) the sustainability of an individual system; and (2) the effect of neighbouring systems on each other. Both of these effects are observed in an area of the Carbonate Rock Aquifer beneath Winnipeg in Manitoba, Canada, where groundwater has been exploited in thermal applications since 1965. In this area, there are four systems that utilize groundwater for cooling purposes that are closely spaced. The current temperatures observed in this area of the Carbonate Rock Aquifer and the results of the numerical modeling conducted in this study confirm that in each system, temperatures at the production well have risen as a result of breakthrough of injected water. The results of numerical modeling also indicate that interference effects are present in three of the four systems examined in this study. The influence of these systems on each other implies that these systems have a spacing that is smaller than the optimum spacing for such systems, and indicates that there is a limit to the density of development that can occur in a given aquifer.

Résumé Deux questions se posent lors de l'utilisation des eaux souterraines à des fins thermiques: (1) la durabilité des systèmes individuels; et (2) l'effet réciproque de systèmes voisins. Ces deux effets sont étudiés dans une zone de l'Aquifère carbonaté sous Winnipeg, dans le Manitoba au Canada, où les eaux souterraines ont été exploitées pour des applications thermiques depuis 1965. Dans cette zone, quatre différents systèmes utilisant l'eau souterraine pour le refroidissement, sont situés à proximité les uns des autres. Les températures actuelles observées dans la zone de l'Aquifère Carbonaté et le résultat de modélisation numérique confirment que chaque système, les températures au droit des puits de production a augmenté, résultat de l'injection d'eau dans le sol. Les résultats de la modélisation numérique indiquent également qu'il existe des interférences entre 3 des 4 systèmes étudiés. L'influence de ces systèmes, les uns sur les autres, implique que ces systèmes sont situés à une distance plus petite que l'espace optimal pour de tels systèmes, et indique par ailleurs qu'il devrait exister une densité limite pour un aquifère particulier.

Resumen El uso a largo plazo del agua subterránea con fines termales da lugar a dos problemas: (1) la sostenibilidad del sistema individual; y (2) el efecto de sistemas vecinos uno con otro. Ambos de estos efectos se observan en un área del Acuífero de Roca Calcárea de Winnipeg, Manitoba, Canadá, donde el agua subterránea se ha explotado para aplicaciones termales desde 1965. En esta área existen cuatro sistemas que utilizan agua subterránea con propósitos de enfriamiento y que tienen espaciamiento cercano. Las temperaturas actuales observadas en esta área del Acuífero de Roca Calcárea y los resultados del modelo numérico llevados a cabo en este estudio confirman, que en cada sistema, las temperaturas del pozo de producción han ascendido como resultado de la penetración de agua inyectada. Los resultados del modelo numérico también indican que los efectos de interferencia están presentes en tres de los cuatro sistemas examinados en este estudio. La influencia de estos sistemas entre ellos mismos implica que los sistemas tienen un espaciado que es menor al óptimo, e indica que existe un límite para la densidad de desarrollo que puede ocurrir en un acuífero dado.

Keywords Groundwater-source cooling · Heat transport · Injection wells · Sustainability · Numerical modeling

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Contaminación termal y simulaciones post-desarrollo de sistemas geotermiales de baja temperatura en Winnipeg, Canadá

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Introduction

Interest in the use of groundwater for thermal applications is growing as a result of a general demand for alternative sources of energy and a search for methods that improve the efficiency of energy use. However, there have been few studies that have examined the impacts on aquifers as a result of these developments after several or many years of operation. For example, a select number of developments in high-temperature geothermal reservoirs have been analysed after an extended period of operation (e.g. Bodvarsson et al. 1990; Mannington et al. 2004), but there have been few published audits of low-temperature applications. Note that post-development models may be much more robust due to the availability of data for calibration purposes. Conversely, creation of such models can be complex due to variability in pumping rates and injection temperatures. In either case, these models will be beneficial because they will enable an assessment of how well we are able to predict aquifer temperatures, and help identify gaps in the required data. Examinations of areas that have been subject to thermal development for many years also provide insight into the long-term behaviour of these developments. The resulting models will assist in developing regulations that will ensure the sustainability of groundwater-source cooling and will also help in the design of monitoring schemes for these developments.

In a typical low-temperature geothermal system, thermal effluent produced by either heating or cooling processes is injected back into the same aquifer from which it was produced. This practice generally affects temperature at the production well of the same system after a period of time and may also interfere with the performance of other nearby systems in the same aquifer. While research directed towards high-temperature geothermal developments has provided a great deal of insight, the problems mentioned above are somewhat unique to low temperature use because of the small size of systems involved and the ability of individual property owners to operate systems.

Note that the following paragraph is written from a thermal-cooling perspective, but, without loss of generality, the discussion is equally valid for heating applications. Developments of groundwater resources for thermal applications can be unsustainable (and even fail) for three basic reasons: (1) insufficient water supply; (2) increases in temperature at a production well due to injection of warm water in an individual system; and (3) increases in temperature at the production well due to injection at neighbouring systems. Water supply issues have been studied extensively in many different contexts and are not as crucial in the case of thermal applications because most systems are non-consumptive. The issue of changing production well temperatures within an individual system is in the interest of the individual user and does not necessarily need to be addressed by government regulators. However, increases in production well temperature due to injection in a neighbouring system should be addressed by regulators and the issue of spacing between individual systems will become increasingly important if

there continues to be an increase in the number of groundwater-source heating or cooling systems (see also Ferguson and Woodbury 2004).

In this study, the effects of groundwater well spacing have been examined in an area of the Carbonate Rock Aquifer beneath the Birchwood area of Winnipeg, Manitoba (Fig. 1) that has been developed for cooling applications. Groundwater is used for thermal purposes on four separate properties in the study area, with developments beginning in 1965. Render (1981) conducted a study of the systems in this area and predicted that further rises in temperature would lead to the thermal degradation and eventual failure of groundwater-source cooling in this area. In this study, numerical simulations are produced to determine the effect of spacing between individual injection-withdrawal doublets and assess the importance of advective heat transport in fractures present in this aquifer. Note that numerical modeling is capable of solving for the entire temperature field and can account for complex boundary conditions, problem geometries, variations in sources and sinks with time and heterogeneities in material properties. METRA, which is a submodule of the MULTIFLO program developed by Painter and Seth (2003), was used for all numerical simulations conducted in this study (see also Ferguson 2004). METRA is a three-dimensional non-isothermal flow simulator that solves a mass balance equation for water and an energy balance equation. Both advective and conductive heat flow are considered by this code. MULTIFLO uses a fully implicit integral finite volume approach and uses a block centred grid for the discretization of the flow domain. The code solves the governing equations for groundwater flow and heat flow iteratively so that the appropriate fluid density and viscosity are used in each cell of the model (Painter and Seth 2003).

Simulations with METRA can be based on either single continuum or dual continuum approaches, but it was uncertain at the start of this study which would be more appropriate for the Carbonate Rock Aquifer. Groundwater flow in fractured rock can be treated in various manners in accordance with the scale examined and the degree of uniformity in the fracture system.



Fig. 1 Location map

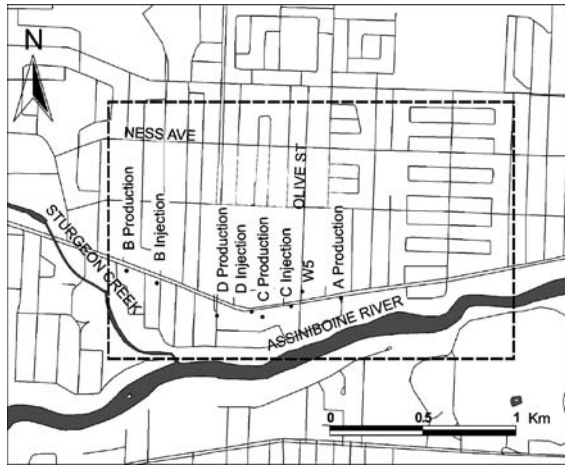


Fig. 2 Location of production and injection wells in the Birchwood area of Winnipeg. The dashed line indicates the boundaries of the modeled area

Berkowitz (2002) suggests that all treatments of fractured media fall into two broad categories of discrete fracture models or continuum models. Discrete fracture models can explicitly account for the effects of individual fractures on fluid flow or transport. These types of models are generally applied to smaller scale problems, where fracture locations and properties can at least be moderately well constrained. Continuum models can be used where a fracture network is dense and a representative elementary volume (REV) can be defined. This group of models includes equivalent single continuum models (SCMs) and dual continuum models (DCMs), which are commonly applied to far field problems. Both SCMs and DCMs will be applied to the Carbonate Rock Aquifer in the current study.

Local hydrogeology

As mentioned, Render (1981) conducted a study of the thermal sustainability of using groundwater in cooling systems in an area of Winnipeg by mapping the potentiometric surface, conducting pump tests in all production wells and examining available temperature data. Results of pump tests conducted during that study suggested that transmissivity ranged from 228 to 1,022 $\text{m}^2 \text{day}^{-1}$, which corresponds to a permeability of approxi-

Table 1 Records available from Manitoba Water Branch for groundwater use in an area of western Winnipeg, Manitoba (after Render 1981)

System	Estimated withdrawal rate (L/s)	Year system installed	Year production well temperature recording began
A	19	1965	1965
B	16	1973	1976
C	19	1973	1976
D	28.5 ^a	1977	2002

^a System D recharges only a portion of the water withdrawn and it is estimated that the injection rate is only 22.2 L/s

mately 10^{-11} m^2 , if it is assumed that the entire thickness of carbonate rock in the area is equally permeable. The analysis conducted by Render (1981) used the Theis (1935) solution, which assumes a homogeneous and isotropic porous medium. However, Render (1981) also noted that there were several discrete fracture zones within the aquifer that may be responsible for most of the permeability. The presence of fractures is also supported by data from these pump tests, which shows a departure from the Theis solution later in the pump tests. This response is most likely related to the delayed response of matrix permeability in this fractured medium (Moench 1984). The fractured nature of the rock in this area is supported by the drilling logs for each of the wells. Although the location of a few of the major fractures is known, their hydraulic characteristics are not well understood.

Underlying the Carbonate Rock Aquifer is the Winnipeg Formation, which contains a regional sandstone aquifer (Betcher 1986). However, there is a layer of shale between the Winnipeg Formation and the overlying carbonate rocks of the Red River Formation that acts as an effective hydraulic barrier between the two units. Similarly, a layer of till overlies the Carbonate Rock Aquifer and this till is overlain by a thick layer of glaciolacustrine clay, both of which have relatively low permeability (Day 1977; Pach 1994) and can be considered impermeable relative to the Carbonate Rock Aquifer for the purposes of modeling.

History of development

In an area of western Winnipeg, four buildings use large amounts of groundwater from the Carbonate Rock Aquifer for cooling purposes (Fig. 2; Table 1). These systems are primarily used for air conditioning during the summer months. The first of these systems (A) was installed in 1965. This system is a consumptive user as the thermal wastewater is discharged to the Assiniboine River. In 1973, two non-consumptive systems were installed at B and C. The final system in the area (D) was installed 4 years later. However, this system is somewhat different from those at B and C in that it operates throughout the year and is only a partially consumptive system. All of the wells installed in this area of Winnipeg are completed as open holes in the carbonate rock at depths between approximately 23 and 122 m.

Numerical modeling

Two numerical models of the Birchwood area were produced to develop a better understanding of the sustainability of the use of groundwater in cooling systems in this area. The hydrostratigraphy of the area has a uniform cross-section with an upper aquifer, an intermediate zone of lower permeability (middle unit), a lower aquifer and a lower zone of low permeability (lower unit; Fig. 3). Both the SCM and DCM were created using

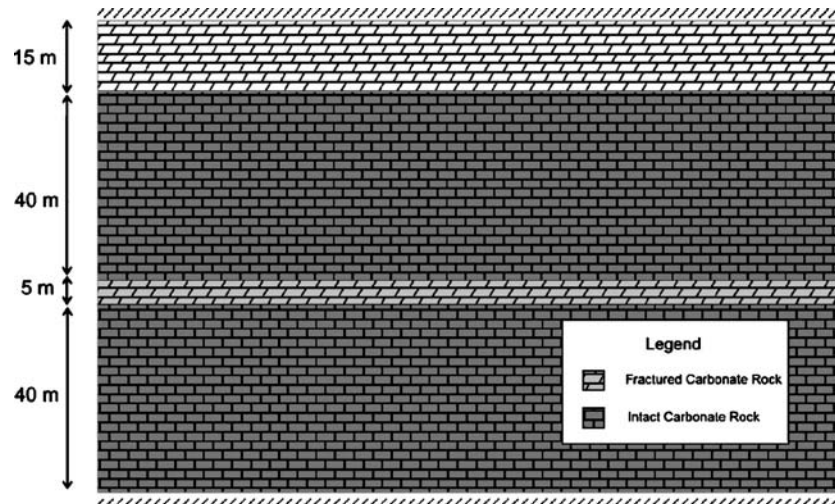


Fig. 3 Hydrostratigraphy of the Birchwood area, showing an upper aquifer, an intermediate zone of lower permeability (middle unit), a lower aquifer and a lower zone of low permeability (lower unit)

this hydrostratigraphy and associated parameters outlined in Table 2. Permeability values used in this study were derived from estimates of transmissivity given by Render (1981). In the case of the DCM, fracture permeability values were estimated using Snow's (1969) method. The data used in the simulations included the aforementioned transmissivity in combination with estimates of fracture porosity given by Render (1970) and McCabe et al. (1993) and a typical value for matrix permeability for limestone (Freeze and Cherry 1979). It should also be noted that little is known on the hydraulic properties of the fracture skin in the Carbonate Rock Aquifer. In modelling performed in this study, direct coupling between the fractures and the matrix was assumed although in some locations there is some infilling of fractures with till and gypsum. Other parameters used in this study are given in Table 2 (see also Schon 1996). Note that in this study, thermal conduction is solely responsible for thermal-macro dispersion. This is consistent with the results of Bear (1972), who shows mathematically that hydrody-

namic dispersion is important in thermal transport only when groundwater velocities are extremely high. Anderson (2005) provides a brief review of this issue.

The location of the Birchwood area extends from the Assiniboine River in the south to north of Ness Avenue, and from Sturgeon Creek in the west to several hundreds of metres west of Olive Street (Fig. 2). Fixed head boundary conditions were placed along the Assiniboine River at the south end, along Sturgeon Creek in the southwest, and along the northern boundary of the study area, which was placed 1,400 m north of the Assiniboine River. The hydraulic head used for the constant head boundary was 222 m, which is approximately the elevation of the Assiniboine River. The eastern boundary and the section of the western boundary north of Sturgeon Creek were assigned impermeable boundaries based on the observation that regional groundwater flow is from north to south. The upper and lower surfaces of the carbonate rock unit were also treated as impermeable boundaries based on the relatively low permeability of the

Table 2 Thermal and hydrogeologic properties used in the calibrated conventional porous media (single continuum) and dual continuum models of the Birchwood area of Winnipeg

	Porous media model				Dual continuum model			
	Upper aquifer	Middle unit	Low aquifer	Lower unit	Upper aquifer	Middle unit	Low aquifer	Lower unit
Matrix permeability (m ²)	1.0×10 ^{-10a}	1.0×10 ^{-12a}	1.0×10 ^{-11a}	1.0×10 ^{-12a}	1.0×10 ^{-12b}	1.0×10 ^{-13b}	1.0×10 ^{-13b}	1.0×10 ^{-13b}
Fracture permeability (m ²)	N/A	N/A	N/A	N/A				
Matrix porosity	0.095 ^c	0.095 ^c	0.095 ^c	0.095 ^c	0.095 ^c	0.095 ^c	0.095 ^c	0.095 ^c
Fracture Porosity	N/A	N/A	N/A	N/A	0.05			
Thermal conductivity (W m ⁻¹ °C ⁻¹)	2.4 ^c	2.4 ^c	2.4 ^c	2.4 ^c	2.4 ^c	2.4 ^c	2.4 ^c	2.4 ^c
Heat capacity (J kg ⁻¹ °C ⁻¹)	1,200 ^d	1,200 ^d	1,200 ^d	1,200 ^d	1,200 ^d	1,200 ^d	1,200 ^d	1,200 ^d

^a Render 1981

^b Freeze and Cherry 1979

^c Ferguson 2004

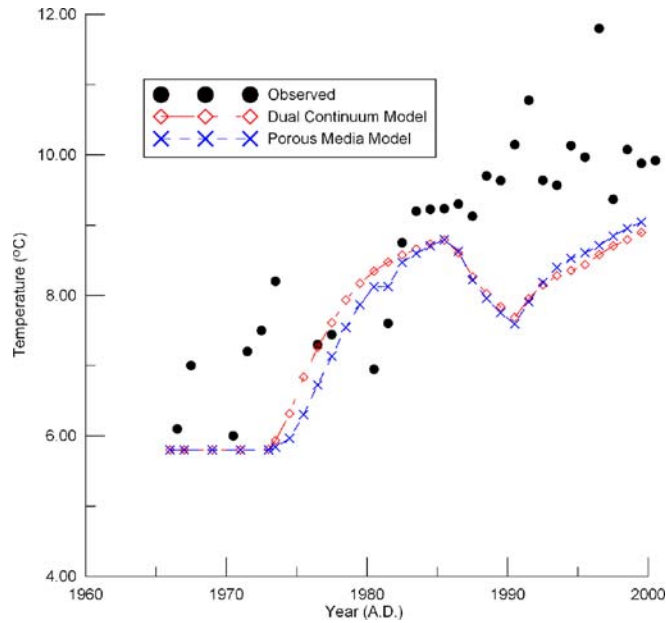


Fig. 4 Measured and modeled temperatures at the production well at system A

overlying till and underlying shale compared to the carbonate rock. Conductive heat losses were allowed at all boundaries. The size of the numerical grid blocks ranged from 25 m across for the entire southern portion, where injection and production wells were present, to 200 m across in the northern portion of the model, where injection and production wells were absent.

Injection and production rates in the simulations were based on the estimated rates (Table 1) and it was assumed that all wells, with exception of those at system D, were in operation over a 4-month period from the middle of May to the middle of September, but the temporal variability of the injection rates are not well constrained. The wells at

system D are in operation throughout the year (Render 1981). Relatively complete records of production well temperatures are available for systems A, B and C and partial records of injection temperature exist for systems B and C. Injection temperatures at some times and locations had to be estimated based on available data and Manitoba Department of Water Stewardship guidelines (assuming guidelines were followed). The Manitoba Department of Water Stewardship regulations allow for a maximum increase of 5 °C in injected water relative to background groundwater temperatures. Modeling was further complicated by a period during which operation of the system D ceased over a 4-year period in the late 1980s. Conse-

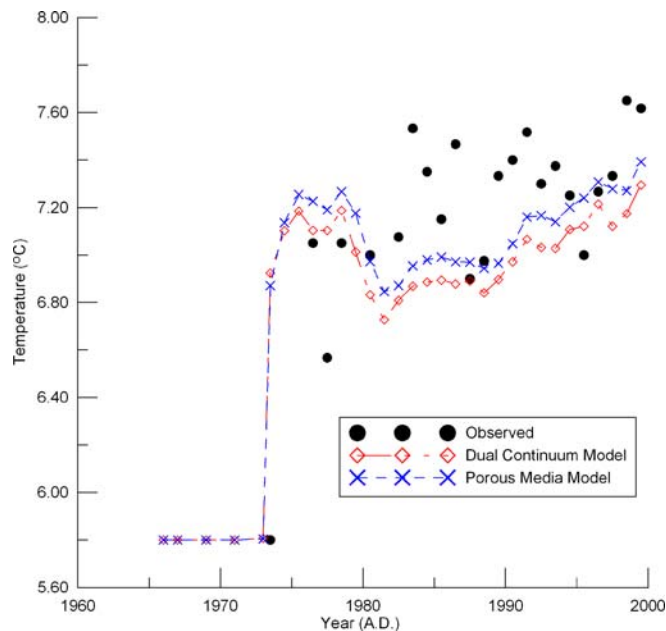


Fig. 5 Measured and modeled temperatures at the production well at system B

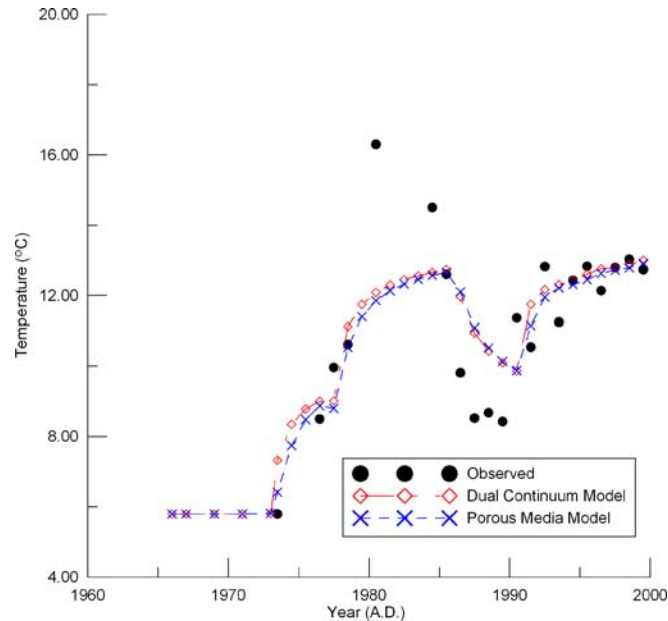


Fig. 6 Measured and modeled temperatures at the production well at system C

quently, an injection rate of zero was assigned from the fall of 1985 to the summer of 1990.

Both conceptual models (SCM, DCM) did a reasonable job of recreating both the general trends observed in the temperature records and the magnitude of temperature increases at each of the production wells with long-term records but are unable to reproduce the highest temperatures observed (Figs. 4, 5, and 6). A reasonable fit was obtained for the calibrated SCM, with an R^2 correlation coefficient of 0.75 for a best-fit line between the predicted and observed temperatures (T) in all three wells described by the following equation:

$$T_{\text{predicted}} = 0.82T_{\text{observed}} + 1.16 \quad (1)$$

The root mean squared (RMS) error between the predicted and observed temperature was 0.14 °C. An overall R^2 correlation coefficient of 0.76 was achieved between all predicted and observed temperatures in the DCM and the best-fit line between the observed and predicted data has the following equation:

$$T_{\text{predicted}} = 0.85T_{\text{observed}} + 0.96 \quad (2)$$

The RMS error between the predicted and observed temperature was 0.14 °C. In both the SCM and DCM, temperatures were underestimated, perhaps due to underestimation of injection temperatures at late times in the model. Sensitivity analyses were conducted for both conceptual models and in both cases it was found that the results were relatively insensitive to changes in permeability and porosity over the expected range for this area. The results were slightly more sensitive to changes in pumping rates but these are well constrained relative to the hydrogeological inputs.

The SCM and DCM produce the same general trends for the system A production well (Fig. 4). Predicted temperatures are approximately 0.3 °C greater in the dual continuum model during the first few years of the simulation. At later times, the conventional porous media model produced slightly greater temperatures. The predicted temperature increase at system Ds production well was similar to the magnitude of the observed temperature increase. However, an interruption in the injection of water to the aquifer during the late 1980s produced a drop in predicted temperatures in the model, which was not observed in the actual temperature record. Instead, the observed temperatures continued to increase during this period. Temperatures increased throughout the 1990s in both the observed and predicted temperatures but the predicted temperatures were generally less by approximately 1.0 °C during this period. This is likely due to increases in injection temperature following breakthrough of warm water at the production well. These increases were not well characterized by the irregular instrumental record and were difficult to estimate given the complex patterns of production and injection.

The SCM and DCM predict similar trends for the production well B (Fig. 5). The SCM predicts temperatures that are approximately 0.1 °C greater throughout the model following thermal breakthrough, which occurred circa 1975. The magnitude of the temperature increase observed in both the predicted and observed records for the production well at system B are similar. However, it is difficult to determine whether the breakthrough times agree between the modeled and observed temperatures because no observations are available until after breakthrough, with the exception of the temperature measurement made immediately after the well was completed. The observed temperatures are generally greater than the predicted temperatures at this location

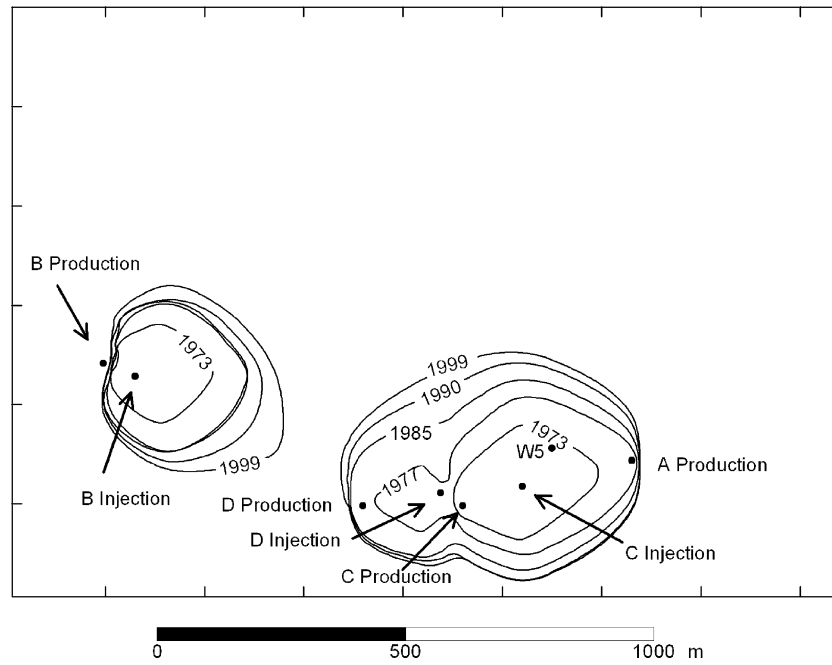


Fig. 7 The predicted evolution of the temperature anomaly over time using the dual continuum model, as shown by movement of the 7 °C isotherm between 1973 and 1999

by a few tenths of a degree Celsius and the amount of variability is less than that present in the simulated record.

There is little difference between predicted temperatures in the SCM and DCM for the production well at system C (Fig. 6). Breakthrough time and the magnitude of the temperature increase are in good agreement for the production well at system C. The model also recreates the

cooling trend observed in the late 1980s, but the response to the interruption of injection at the system D is slower and has a less dramatic effect on predicted temperatures than in measured temperatures. The model is not able to reproduce the temperatures measured in 1981 and 1984, which occur prior to the beginning of temperature measurements in the injection well. These temperatures

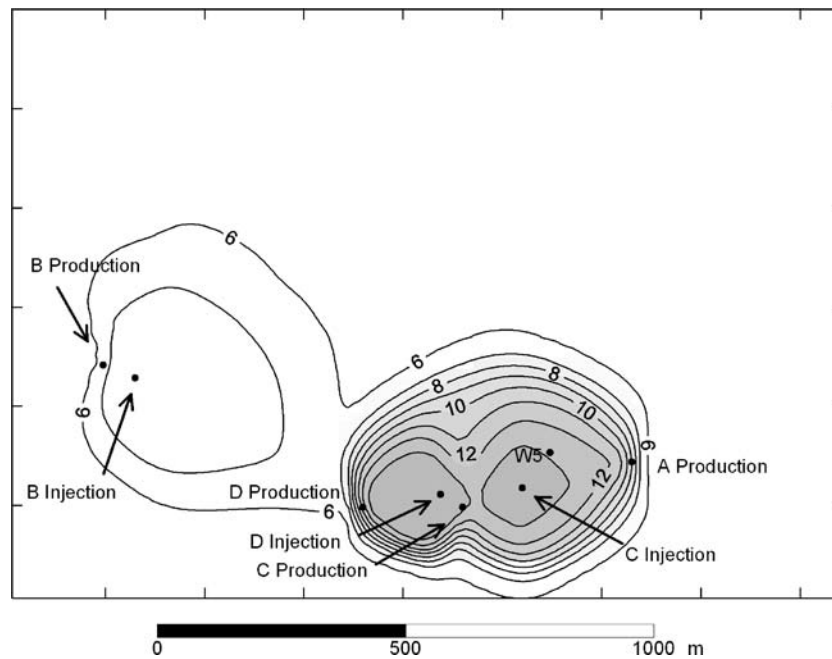


Fig. 8 Temperatures (°C) predicted in the Upper Carbonate Aquifer by the calibrated dual-continuum model for 1999. Areas of higher temperatures are shown as darker areas on the contour plot

exceed the Province of Manitoba's maximum injection temperature requirements.

The spatial distribution of the predicted temperature anomaly was essentially the same in the conventional porous media and dual continuum model and, as a result, only maps of temperatures predicted by the dual continuum model are presented (Figs. 7 and 8). The first anomalies appear in the vicinity of the wells at systems B and C, which were the first injection wells to begin operation in the area. The predicted anomaly around C is approximately symmetric, as it appears to be affected by production at both systems A and B. (Fig. 7). The anomaly at B is also slightly skewed in the direction of the production wells to the east. In 1977, system D was brought into operation, resulting in a change in the predicted temperature field (Fig. 8). After only a few months of operation, the predicted temperature anomaly due to injection at system D has coalesced with the anomaly from system C. The interior of these estimated anomalies stabilized at this point and only slight outward growth occurs after this time. By 1985, the temperature anomaly from system B is predicted to have coalesced with the anomaly associated with the other three systems (Fig. 7). The predicted temperature anomaly had a slightly different shape in 1990 following an absence of production and injection at system D and the subsequent resumption of operation. Predicted temperatures in 1999 (Fig. 8), which marks the end of the simulated period, were very similar to those observed in 1985, suggesting that this is a quasi-equilibrium state for the system. These predicted temperatures appear to adequately simulate what occurs in this area for the systems at systems B, C and D. The predicted temperatures shown in the vicinity of system A are not in good agreement with the temperature record at system A or with the measured temperature at monitoring well W5, which was approximately 9.0 °C in 2002. Acquiring more data on the fracture network, which controls the distribution of permeability in this aquifer, may assist in rectifying this discrepancy.

Few hydraulic head data are available for the Birchwood area. Render (1981) provides a map of the potentiometric surface from 1980 but these data are likely not accurate as they were derived from production and injection wells that were in operation at the time. These measurements are subject to error because the well efficiencies for these wells are unknown and this can lead to significant decreases (or in the case of injection increases) in the water level measured in a well. Also, hydraulic head is known to vary significantly throughout the year in the Upper Carbonate Aquifer due to natural influences (Render 1970; Rutulis 1989; Ferguson and St. George 2003) and these forcing mechanisms are not considered in this model. Finally, actual rates in these systems will vary depending on the demand for air conditioning which will be quite variable during the summer. This level of variability is not represented in the pumping rates used in model and this would likely cause difficulties in calibrating the model to measured hydraulic head data, if a sufficient amount were available.

Discussion

Both SCM and DCM formulations provided reasonable results in the reconstruction of groundwater temperatures in the study area. There appears to be no significant advantage to either formulation, but it is strongly suspected that given more data the use of a dual continuum formulation would be more appropriate. This idea is supported by the lack of response in the production well of system A to changes in pumping in nearby wells. The absence of the expected response can likely be attributed to a reduction in permeability, which is strongly linked to the presence or absence of fractures in this aquifer. This relationship likely indicates that there is discontinuity in the fracture network between the systems A and C. In addition to this lateral variability within a hydrostratigraphic unit, the definition of the hydrostratigraphic units in this study was done on the basis of the frequency of fractures, which suggests that if the study had been able to better characterize the fracture network, a DCM formulation would produce superior results. However, at this stage it must be conceded that the SCM performed as well as the DCM and it may be preferable to use this simpler formulation.

Although the amount of temperature data available in this study is substantial, there are several areas where data are lacking. Temperature data are most scarce during the early periods of pumping and are more abundant later on. This is discordant with data requirements in this type of study as the maximum rate of temperature change occurs early during the operation of these systems. Hydraulic head measurements would also be useful in further constraining any numerical models created. However, this hydraulic head data must be nearly continuous in time, with readings taken several times a day, in order to address the diurnal and seasonal variability in withdrawal and injection rates related to cooling demands. Measurements taken less frequently would be of little use because it is unlikely that they will be representative.

The operation of the wells at system B appears to have little effect on the temperatures in the vicinity of the other wells. Analysis of this system in isolation would likely produce similar results. However, this is not the case with the other three systems. These three systems all impact one another and this is very apparent in the temperature records at systems C and D. System A is consumptive and therefore no increases in temperature were observed during the first 8 years of operation at this site. However, immediately after the beginning of operation at system C, temperature increases were observed. A similar feature was observed in the temperature record for system C production well after system D came into operation in 1977. The rate of temperature increase at the production well at system C was dropping in 1975 and 1976 but increased sharply in 1977. Later changes in production patterns had similar effects on the three eastern systems.

Increases in temperature in these systems were inevitable regardless of their positioning relative to each other due to the imbalance in thermal loading on the aquifer.

Similar issues will arise in aquifer thermal energy (ATES) systems, where more attention is given to sustainability of both temperature and water supply because it must be possible to recover injected water at specific times in order to meet heating or cooling needs. This is difficult to accomplish due to variability in heating and cooling demands and geological uncertainty. The addition of other ATES systems nearby will add extra complexity to this issue by involving a greater volume of aquifer, which will increase the potential for heterogeneity to become an issue. Additional systems will likely have different heating and/or cooling demands, resulting in different usage patterns than those in the original system. From the results of this study, it is clear that there is a threshold spacing value that allows for analysis of such a system independent of neighbouring systems. For typical developments in the Carbonate Rock Aquifer, this value appears to be approximately 500 m. However, this value is dependent on several factors including: porosity, permeability, pumping rates, and injection temperatures. Variability present in all of these factors may play a significant role in determining the area of the hydraulic and thermal influence. However, if it is assumed that 500-m spacing is the average value, the development of the Carbonate Rock Aquifer for thermal purposes becomes somewhat limited. If it is possible to develop this aquifer at a density of four systems per km², only a small percentage of property owners will be able to use groundwater in thermal applications if current development practices continue.

Conclusions

Field observations and numerical modeling in this study have provided insight into the nature of thermal pollution in a portion of the Carbonate Rock Aquifer in Winnipeg, Canada. The fracture network appears to be important due to its effect on the distribution of permeability and likely warrants further investigation in this area and in other future developments in the same aquifer. The modeling exercises carried out during this study have also provided some insight into how to improve data collection. Although reasonable agreement between measured and predicted temperatures was achieved, it is strongly suspected that better results would have been attained if more complete records of injection rates and temperatures were available. More detailed information on hydraulic head distribution, both in time and space, would have also resulted in the creation of a more robust model.

The current temperatures observed in this area of the Carbonate Rock Aquifer and the results of the numerical modeling conducted in this study indicate that the groundwater-source cooling systems in this area are unsustainable and inefficient. In each system, temperatures at the production well have risen as a result of breakthrough of injected water from within that system. The results of numerical modeling help explain the field observations that interference effects are present in three of the four systems examined in this study. This

interference led to greater increases in temperature in two of these wells after the start of operation at the newest system. The influence of these systems on each other implies that these systems have a spacing that is smaller than the optimum spacing for such systems, and indicates that there is a limit to the density of development that can occur in a given aquifer. The arrangement of individual systems relative to each other must be considered during the design process. There is potential for increased use of groundwater for thermal applications in the Carbonate Rock Aquifer but greater attention must be given to allocation of this resource and maximizing the efficiency of its use.

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