Low temperature geothermal resources in the Canadian Shield: The feasibility of using water from flooded mines as an energy source in Northern Quebec

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ABSTRACT

With an average geothermal gradient of 10 °C km^{-1}, the Canadian Shield does not host conventionally attractive geothermal resources. Due to the abundance of abandoned mines that have been flooded by geothermally heated groundwater, however, significant amounts of energy can be extracted at high flow rates. When coupled with heat pump systems, it can be used as an environmentally friendly heating source for nearby infrastructure. The Copper Rand mine, studied for that purpose, is situated near the town of Chibougamau, at the gateway to Northern Quebec. A numerical model was developed to simulate the extraction of water and heat from its underground workings, with reinjection occurring in another mine 2.5 km away. Preliminary results suggest that such a system could offer thermal energy on the order of 10^8 MJ a^{-1} for a production period of 25 years, with a thermal power output exceeding 4 MW.

RÉSUMÉ

Avec un gradient géothermique d'environ 10 °C km^{-1}, le Bouclier canadien ne contient pas de ressources géothermiques conventionnelles. Cependant, plusieurs mines abandonnées ont été inondées par de l'eau réchauffée par la chaleur de la Terre et contiennent des quantités importantes d'énergie. Lorsque couplée avec des systèmes de pompes à chaleur, cette eau peut être utilisée et pompée à débits élevés dans le but de chauffer des infrastructures à proximité. La mine Copper Rand, étudiée dans cette optique, est située près de Chibougamau, à la porte du nord du Québec. Un modèle numérique a été créé pour simuler l'extraction de l'eau et de chaleur des galeries, avec réinjection dans une autre mine abandonnée située à 2,5 km de distance. Les résultats préliminaires suggèrent que l'énergie thermique pouvant être extraite de la mine est de l'ordre de 10^8 MJ a^{-1} pour une période de 25 ans, avec une puissance thermique supérieur à 4 MW.

NOMENCLATURE

β	compressibility (Pa^{-1})
λ	thermal conductivity ($W\ m^{-2}\ K^{-1}$)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
ϕ	porosity *(%)*
C	heat capacity ($J\ kg^{-1}\ K^{-1}$)
E	energy (MJ)
h	hydraulic head (m)
K	hydraulic conductivity ($m\ s^{-1}$)
k	fracture permeability (m^2)
m	mass (kg)
P	power (MW)
p	pressure (Pa)
Q	volumetric heat flux ($W\ m^{-3}$)
q	heat flux ($W\ m^{-2}$)
S_s	specific storage (m^{-1})
T	temperature (K; °C)
t	time (s)
$\mathbf{u}$	mean fluid velocity ($m\ s^{-1}$)
v	volume (m^3)
w	fracture width (m)

1 INTRODUCTION

The towns of Chibougamau and Chapais are situated at the gateway to Northern Quebec (Figure 1). Less than 50 km apart, they are the two largest settlements in the region, with current populations of 7000 and 1300, respectively (Statistics Canada, 2017). The region was a prolific mining centre during the 20th century, with over 25 mines producing gold, copper, and silver. Over the past few decades, all of these mines have been closed, causing an exodus of people and investment from the communities (I. Milord, Director of economic development, Développement Chibougamau, personal communication, 24 October 2017). When the mines were shut down and the dewatering systems removed, they became infiltrated with geothermally heated groundwater and now contain considerable energy reserves.

Located in the interior of Quebec, the towns experience cold winters (average daily temperature of -19 °C in January) and mild summers (average daily temperature of 16 °C; Government of Canada, 2017). In this climate, inexpensive and reliable heating is essential for both residents and industry alike. Currently, space heating is provided by pellets, firewood, heating oil, and/or electricity (I. Milord, Directrice de développement économique de Développement Chibougamau, personal communication, 24 October 2017).

The premise of this study was to explore the possibility of using the geothermally heated mine water as an energy source for the communities, either by establishing district heating systems for residential areas, or by inviting industry to establish their infrastructure in close proximity to the mines. The region as a whole was considered, with

Figure 1: Locations of Chapais and Chibougamau, north of the 49° parallel, marking the lower boundary of Northern Quebec (figure produced with SIGÉOM).

information gathered on all of the abandoned mines in the area. Numerical modelling techniques were used to simulate the heat transfer and groundwater flow processes associated with extracting water from 20 of these mines, with the aim of determining the amount of energy that could be sustainably extracted over a 25 year period. This paper focuses on the results of the largest and deepest mine in the region, the Copper Rand mine, where water could be extracted from the main shaft and reinjected into the Cedar Bay mine, 2.5 km away.

2 BACKGROUND INFORMATION

2.1 Geothermal energy

In geothermally favourable areas, energy drawn from the subsurface can be used to satisfy both electrical and heating requirements. Conventional geothermal electricity production requires the presence of a high-grade resource, defined by subsurface fluids at temperatures exceeding 150 °C within 3 km of the surface (Tester et al., 2012). Finding these temperatures at shallow depths requires specific geologic conditions, such as hot spots or the recent intrusion of magma bodies near to the surface.

For regions that lack high-grade resources, lower temperatures (>80 °C) can be viable for small-scale electricity production, particularly in regions where alternative energy sources are expensive or unreliable (e.g. remote arctic communities; Chena Power, 2004).

Fluids at temperatures of 60-120 °C can be used for direct heating (Tester et al., 2012), while lower temperatures can provide heat when used in conjunction with heat pumps. These low temperature resources can also be used for cooling during the warm summer months. In addition to temperature requirements, geothermal resources must contain sufficient volumes of flowable fluids to provide sustainable energy (Grasby et al., 2012).

2.2 Heat pump thermodynamics

The most suitable system for extracting groundwater from a flooded mine is an open loop system, where warm groundwater is pumped to the surface, a portion of the thermal energy is extracted, and the cooled fluid is returned to the aquifer (Figure 2). A heat exchanger is used to transfer heat from the subsurface fluid to a carrier fluid, which provides heat to the heat pumps and is less damaging to equipment than the chemically variable subsurface fluids (Kavanaugh and Rafferty, 2014).

Heat pumps operate by cycling a working fluid through a vapour-compression refrigeration cycle (Figure 3). It is heated in an evaporator by the carrier fluid, increasing its entropy and changing into a gaseous phase (stage 2). The gas is compressed, increasing its temperature until it is warmer than the desired temperature of the infrastructure to be heated (stage 3). The working fluid circulates through the infrastructure, diffusing heat into the environment and warming it. During this process, the working fluid cools and returns to a liquid state (stage 4). The liquid passes through an expansion valve, returning to its initial temperature, pressure, and entropy conditions (stage 1), and is recirculated through the process.

2.3 Geologic setting

Chibougamau and Chapais are situated within the Superior geological province of the Canadian Shield, within the Abitibi belt. Archean volcanic complexes and smaller intrusives cross-cut one another and the sequence has been faulted and metamorphosed. Bedrock is overlain by a thin layer (~20 m) of unconsolidated quaternary deposits.

The town of Chibougamau overlies two volcanic sequences belonging to the Roy Group, from 2.7 billion years ago. A fault to the south-east of town separates the Roy Group from the Doré Lake Complex, composed predominantly of schists, gabbros, and anorthosites. Many of the mines near Chibougamau target this large complex (Leclerc et al., 2017). The bedrock hosting the Copper Rand mine is fractured anorthosite. The town of Chapais is surrounded by the Roy Group and three sills belonging to the Cummings Complex. Faulting and folding have deformed the bedrock (Leclerc et al., 2010).

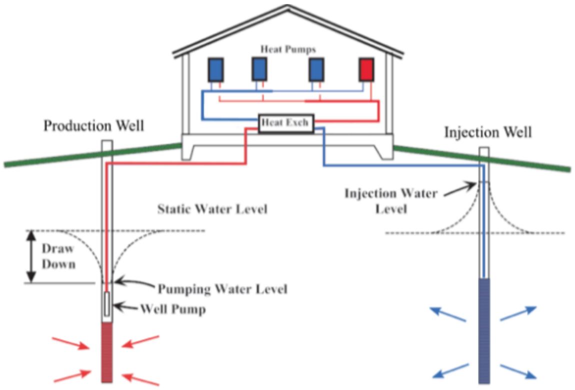


Figure 2: Open loop ground source heat pump schematic. Modified from Kavanaugh and Rafferty (2014) on pg. 5.

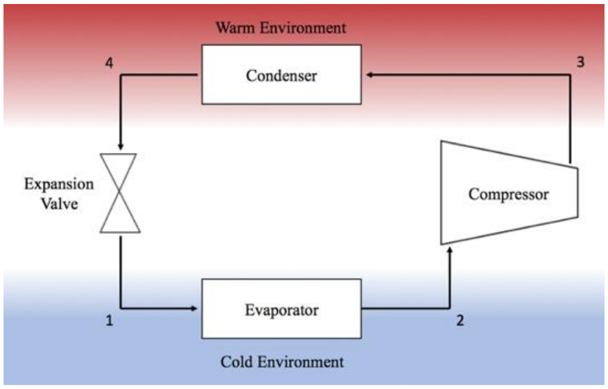


Figure 3: The ideal vapour-compression refrigeration cycle. Based on Çengal and Boles (2006).

Crystalline rocks, such as those found beneath Chibougamau and Chapais, have relatively high thermal conductivities and relatively low geothermal gradients. Internal heat generation through radioactive decay is limited due to the age of the Canadian Shield, further reducing the total heat flux. Temperature profiles recorded in nearby wells indicate there is a relatively constant increase in temperature with depth beyond the uppermost 100 m of the subsurface. These profiles suggest the following geothermal gradients for Chibougamau and Chapais, respectively (Gosselin & Borde, 2004):

$$T = 3.767\ ℃ + 6.975\ ℃\ \mathrm{km}^{-1} \qquad [1]$$

$$T = 4.286\ ℃ + 7.350\ ℃\ \mathrm{km}^{-1} \qquad [2]$$

According to these gradients, temperatures slightly above 7 °C can be expected at 500 m depth in the Chibougamau area, while temperatures of 8 °C can be expected in the Chapais area. Subsurface heat flux in the region is estimated to be 26.5 mW m^{-2}, using an estimated thermal conductivity of 4.0 W m^{-1} K^{-1} based on the region's rock type. This value is lower than the Superior Province average of 32.1 mW m^{-2} (Comeau et al., 2017).

3 MODELLING METHODOLOGY

3.1 Model geometry and properties

A three-dimensional finite element model of the Copper Rand mine and surrounding bedrock was created using the software COMSOL (Figure 4). The model was generated to simulate water and heat extraction, injection, and transfer within the subsurface. In order to reduce the size of the model while preventing interference by lateral boundaries, a simulation was run in a 100 x 100 km model block with a production rate of 2000 kg s^{-1} for a period of 50 years (both higher values than would be used in the final simulations). The pumping radius of influence was evaluated. The drawdown was shown to decrease with distance from the pumping site, and beyond 5 km was less than 1 m. Temperature changes were limited to within a 2.5 km radius of the site. As such, the usable model was conservatively sized at 12 x 12 km in the x and y planes, with a depth of 4 km. For a reduced pumping rate of 25 kg s^{-1} over 25 years, the changes in head exceeding 20 cm were further than 2 km from the edge of the model.

In order to account for changing geophysical properties with depth, shallow and deep bedrock units were created with different porosities and permeabilities (Table 1). The shallow anorthosite spans the uppermost 200 m of the model, while everything beneath it is deep anorthosite.

Due to the computational intensity of representing mine features with discrete model components, the mined area was represented by a rectangular cuboid with increased porosity and permeability, encompassing the volume within which the majority of the mine workings exists. Only the most significant mine structures were added to the model, including a vertical main shaft, a sub-vertical secondary shaft, and a sub-horizontal ramp. These components were modelled as 2D elements and were intended to represent high permeability features within the mine workings.

The production well was situated within the main vertical shaft at a depth of 500 m. The porosity of the mine was calculated volumetrically by considering the porosity of the surrounding bedrock, the total volume of the block, the volume of extracted ore, and by assuming a ratio of waste rock to ore for copper and/or gold mines between 20-30 (as recommended by Mudd, 2007).

Reinjection of water occurred within the Cedar Bay mine, located at a distance of 2.5 km from the Copper Rand mine. Little was known about the geometry of this mine, so it was modelled as a cylinder with a radius of 200 m surrounding a vertical shaft. The vertical shaft was 1000 m deep, with a reinjection well located 100 m beneath the surface. The same thermal and hydraulic properties were applied as in the Copper Rand mine.

3.2 Fluid flow physics

The fluid contained within the subsurface was assumed to be water, with a compressibility of 4.4 x 10^{-10} Pa^{-1}. Transient flow through a saturated anisotropic porous medium was simulated, combining Darcy's Law (Equation 3) with groundwater storage (Equation 4).

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_\mathrm{s} \frac{\partial h}{\partial t} \qquad [3]$$

$$S_\mathrm{S} = \rho g(\beta_\mathrm{m} + \phi \beta_\mathrm{w}) \qquad [4]$$

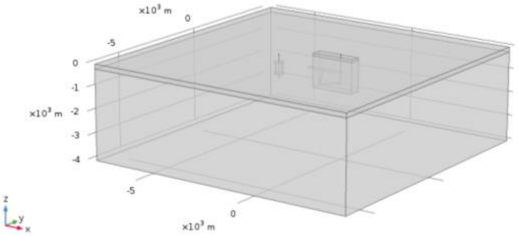


Figure 4: Geometry of the Copper Rand mine model

Table 1: Properties assigned to model components. Permeability, porosity, and density are based on Freeze and Cherry's (1979) recommendations. Thermal conductivity and heat capacity are based on analyses conducted on rock samples taken from the mine.

	Shallow Anorthosite	Deep Anorthosite	Copper Rand Mine
Dimensions (km)	12 × 12 × 0.2	12 × 12 × 3.8	2.4 × 0.75 × 1.4
Permeability (cm^2)	5×10^{-8}	1×10^{-8}	1×10^{-5}
Porosity (%)	10	6	57
Density (kg m^3)	2.71×10^3	2.71×10^3	2.71×10^3
Thermal Conductivity (W m^{-1} K^{-1})	2.874	2.874	2.874
Heat Capacity (J kg^{-1} K^{-1})	937	937	937

The term K (m s^{-1}) is the hydraulic conductivity and h (m) is the hydraulic head (Freeze and Cherry, 1979). S_S (m^{-1}) is the specific storage. β is compressibility, where subscript m is the matrix (1 x 10^{-9} Pa^{-1}) and w is water (4.4 x 10^{-10} Pa^{-1}; Fetter, 2000). ϕ (%) is porosity.

Fracture flow was applied to the discrete mine components and used a variant of Darcy's law wherein tangential derivatives defined flow along interior boundaries representing fractures within the porous media (Equations 5 & 6; COMSOL, 2017).

$$w\dot{m} = w\frac{\partial}{\partial t}(\phi\rho) + \nabla_{\mathrm{T}} \cdot (w\rho\mathbf{u}) \qquad [5]$$

$$\mathbf{u} = -\frac{k}{\mu}\nabla_{\mathrm{T}} p_2 \qquad [6]$$

where w is the fracture thickness, defined in this case as 10 m, $\dot{m}$ (kg m^{-3} s^{-1}) is the mass source term, ϕ (%) is the fracture porosity, ρ (kg m^{-3}) is the fluid density, ∇_T is the gradient operator of the fracture's tangential plane, and **u** (m s^{-1}) is the mean fluid velocity, where k is fracture permeability (m^2), μ (Pa s) is the fluid dynamic viscosity, and p (Pa) is pressure. The porosity within the fracture is set to 100% and the permeability is set to 100 cm^2.

3.3 Heat transfer in porous media

Total heat transfer Q (W m^{-3}) was composed of conductive heat transfer through the solid bedrock and advection of the fluid within the subsurface pores (Equations 7-9). Flow coupling was applied, allowing fluid movement to affect the dispersion of heat within the system.

$$Q = (\rho C)_{\mathrm{eff}}\frac{\partial T}{\partial t} + \rho C\mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q}' \qquad [7]$$

$$(\rho C)_{\mathrm{eff}} = \phi\rho_{\mathrm{f}}C_{\mathrm{f}} + (1 - \phi)\rho_s C_s \qquad [8]$$

$$\mathbf{q}' = -\lambda\nabla T \qquad [9]$$

ρ is density (kg m^{-3}), C is heat capacity (J kg^{-1} K^{-1}), and the subscript eff is effective. T is temperature (K), t is time (s), **u** is the velocity field computed by the Darcy's Law interface (m s^{-1}; Equation 6), and **q'** is the conductive heat flux (W m^{-2}). Subscripts f and s refer to the fluid and solid phases, respectively. λ is the effective thermal conductivity (W m^{-2} K^{-1}), determined by testing rock samples extracted from the mine (COMSOL, 2017).

Heat transfer was modelled for the mine components, incorporating convection within the subsurface fluids (Equation 10).

$$w(\rho C)_{\mathrm{eff}}\frac{\partial T}{\partial t} + w\rho c\mathbf{u} \cdot \nabla_{\mathrm{t}} T + \nabla_{\mathrm{t}} \cdot \mathbf{q}' = wQ + q \qquad [10]$$

where Q is a possible heat source (W m^{-3}) and q is the out-of-plane heat flux (W m^{-2}) entering the area of interest. Heat enters the system at the injection well (Equation 11).

$$Q_{\mathrm{l}} = C(T_{\mathrm{inj}} - T_{\mathrm{res}})\dot{m}_{\mathrm{l}} \qquad [11]$$

where Q_l is a line heat source (W m^{-2}), applied on a cylinder of radius 1 m (the well radius) around the line. T_{inj} is the temperature of the injected water, T_{res} is the existing reservoir temperature, and $\dot{m}_{\mathrm{l}}$ is the injection mass flow rate (kg m^{-2}). The injected water is set at 276 K (sufficiently warm to prevent freezing during transportation/injection), less than the ambient reservoir temperature (as defined by Equation 1), signifying that Q is a negative value and causes the formation and propagation of a cold front.

3.4 Initial conditions

A hydraulic head of 0 m was set as the initial, undisturbed state of the entire model. No flow boundaries were applied to the top and bottom (neglecting surface water infiltration in the uppermost meters, as Darcy's Law assumes pores are fully saturated). A constant hydraulic head of 0 m was applied to the sides of the model. Internal boundary conditions were created at the locations of the production and injection wells. Mass was extracted and reinjected into the reservoir at a flow rate that was modified in the experimentation process, but began at 100 kg s^{-1}.

The initial geothermal gradient of the model was defined by Equation 1. As such, temperatures exceeded 14 °C in the deepest portion of the mine (over 1500 m). Mine staff reported underground temperatures that exceeded 20 °C (I. Milord, Directrice de développement économique de Développement Chibougamau, personal communication, 24 October 2017). This discrepancy may be due to an increased rate of exothermic mineral oxidation in the mine environment relative to the wells where the temperature measurements were made, a factor that was neglected in the simulations. For the purposes of this model, the geothermal gradient taken from the temperature-depth profiles was used, but it is possible that it is steeper in reality.

The upper boundary of the model was set to a constant 3 °C; the average ground temperature for a depth of 2 m, neglecting seasonal near-surface temperature fluctuations. A heat flux of 0.0195 W m^{-2} was applied to the lower boundary, as determined by iterative forward modelling to maintain the observed geothermal gradient. The sides were assigned as thermal insulation boundaries.

3.5 Simulation mesh and time steps

The simulations were run with an automatically tessellated free tetrahedral mesh, with a minimum unit size of 1.3 m, a maximum size of 2000 m, and a maximum growth rate of 1.3. Time steps were chosen freely by the program. These parameters were selected as they offered the best balance of representativeness and computational intensity.

Simulations were run over a period of 25 years, selected based on the expected lifetime of the heat pump (Grasby et al., 2012). The model was optimized to extract the highest fluid flow rate without:

1. the hydraulic head at the production well dropping beneath -30 m (at which point the required pumping power would be too high)
2. the hydraulic head at the injection well rising above 5 m (at which point injection into the subsurface would be assumed to require compression)
3. the temperature of the produced water falling beneath 278 K

3.6 Energetic calculations

The quantity of heat that can be extracted from the subsurface fluid was calculated with:

$$E_{\mathrm{n}} = v_{\mathrm{n}}(T_{\mathrm{n}} - T_{\mathrm{min}})C \qquad [12]$$

where E_{n} (MJ) is the energy available over time n (analysed over month long intervals in this study), v_{n} (m^3) is the volume of water extracted over the same time period, T_{n} (K) is the fluid temperature, T_{min} (176.2 K) is the minimum temperature to which the fluid would be cooled, and c (4.184 MJ m^{-3} K^{-1}) is the volumetric heat capacity of water. The thermal power P (MW) can be calculated by:

$$P = \frac{E_{\mathrm{n}}}{t_{\mathrm{n}}} \qquad [13]$$

where t_{n} (s) is the time over which the energy will be used.

4 RESULTS

4.1 Regional overview

There are four mines within a 30 km radius of Chapais (some with infrastructure beneath the town itself) and 20 within the same radius of Chibougamau. They range in depth from 84 to 1524 m and produced volumes of ore ranging from 63 000 to 16 000 000 t (Table 2; Figure 5).

4.2 Modelling results

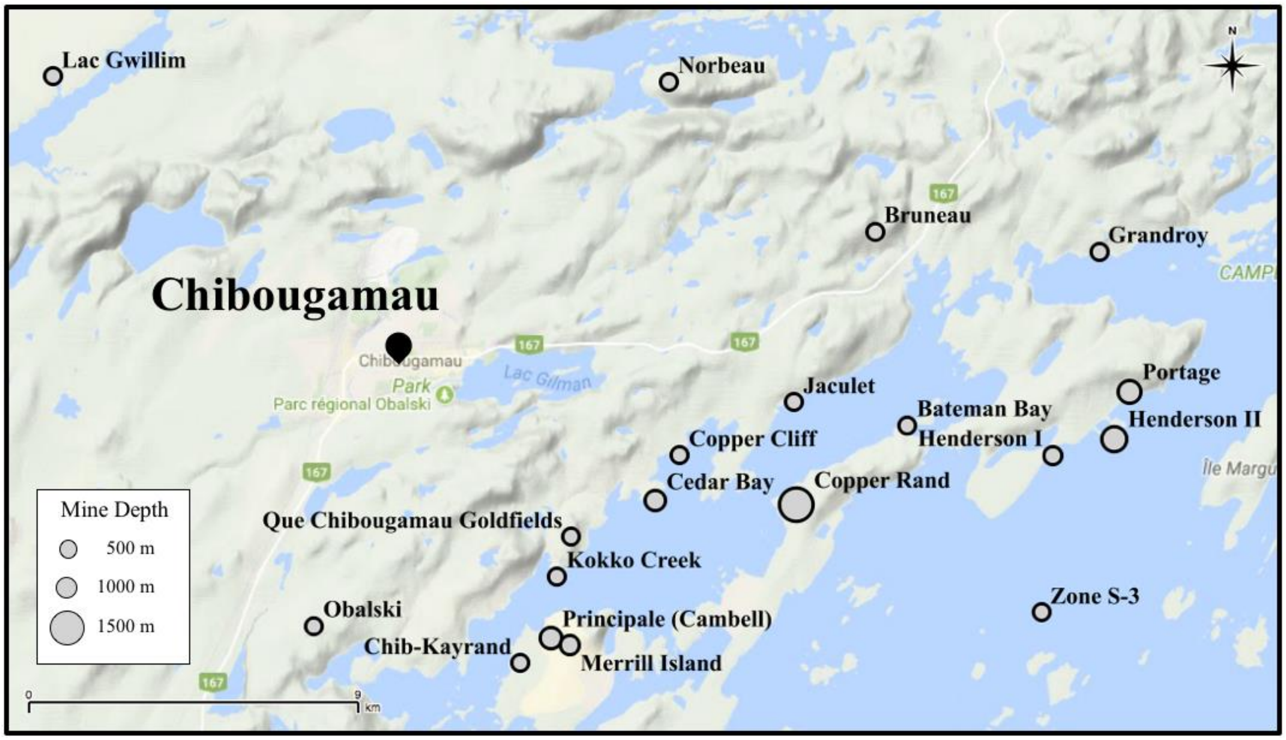
Model optimization indicated that the Copper Rand geothermal system could handle a pumping rate of 160 kg s^{-1} (0.160 m^3 s^{-1}) for a period of 25 years without violating any of the conditions outlined in Section 3.5.

There was a linear relationship between the hydraulic head build up at the injection site and the pumping rate of 0.031 m s kg^{-1}. At a production rate of 160 kg s^{-1}, the head built up to 5.0 m within the first year and remained constant for the remainder of the simulation (Figure 6). This was the factor that limited production. The head draw down at the production site was 1.3 m.

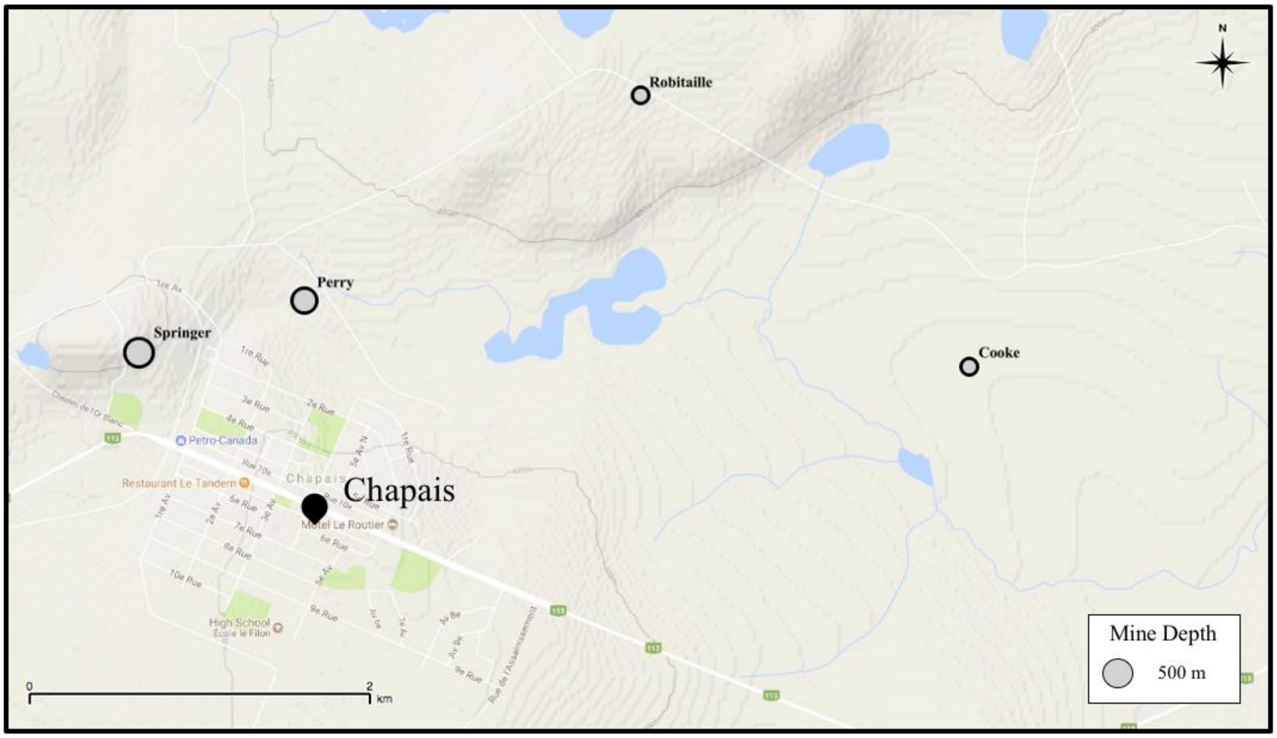
The observed temperatures at the production site (at 500 m depth, partway down a vertical shaft) were between 282.7 K and 283.2 K, higher than the undisturbed

Table 2: Maximum depth and total extracted ore from the mines near Chibougamau (first 22) and Chapais (last four). "-" denotes unknown value (various sources; Arkay, 1992; CBay Minerals Inc, 2015; others).

Mine	Maximum Depth (m)	Total Production (t)
Bateman Bay	274	678 750
Bruneau	233	63 000
Cedar Bay	1000	4 211 000
Chib-Kayrand	-	114 000
Copper Cliff	533	778 000
Copper Rand	1524	16 445 000
Grandroy	-	349 000
Henderson I	305	1 819 000
Henderson II	885	8 316 000
Jaculet	537	1 091 000
Kokko Creek	259	751 000
Lac Gwillim	-	250 000
Lemoine	400	757 000
Merrill Island	701	2 506 000
Norbeau	480	380 000
Obalski	84	98 000
Portage	1200	6 213 000
Principale (Cambell)	670	4 585 000
Que Chibougamau Goldfields	258	212 000
Zone S-3	-	421000
Cooke	470	1 084 000
Perry	496	8 556 000
Robitaille	413	188 000
Springer	500	11 209 000



a)



b)

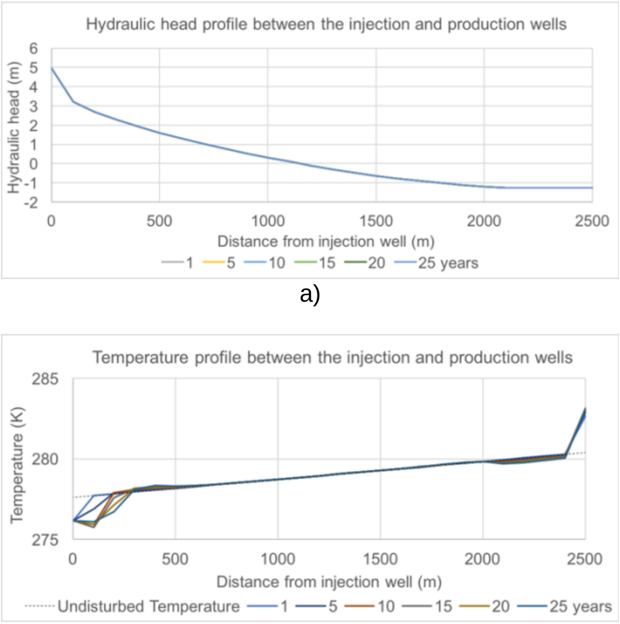
Figure 5: Mines in close proximity to Chibougamau (a) and Chapais (b). Marker size is indicative of the maximum known depth of the mine. The Lemoine mine is out of the frame in Figure a, approximately 40 km SE of Chibougamau.

temperature of 280.4 K based on the geothermal gradient. This temperature anomaly was present within the first month of production (the smallest resolved time interval) and was not observed at the nearest measurement point, 100 m away.

Propagation of a cold front from the injection site occurred over time. The temperature at the injection site remained constant at 276.2 K (the temperature of the injected water). By the 6th year, the temperature 100 m away had dropped more than one degree. In year 23, a one degree temperature decrease was observed 200 m away. At the end of the simulation (25 years), the temperatures 100 m and 200 m from the injection site were 1.7 K and 1.1 K colder than the undisturbed temperatures, respectively. No temperature decrease was observed 300 m from the injection site.

Between the cold front at the injection site and the temperature increase at the production site, there is a gradual increase in temperature corresponding to the geothermal gradient along the downwards trending trajectory between the injection and production wells.

At a production rate of 160 kg s^{-1}, cooling the water to 276.2 K, the system has the capacity to extract 1.37 x 10^8 MJ of thermal energy annually, corresponding to a sustained thermal power output of 4.35 MW.



a)

b)

Figure 6: Hydraulic head and temperature profiles along a straight line (of increasing depth) between the injection and production sites, resolved at 100 m intervals.

5 DISCUSSION AND CONCLUSION

The results of the regional assessment of abandoned mines and simulations of heat extraction from the Copper Rand mine suggest that there are large quantities of extractable energy beneath the towns of Chibougamau and Chapais. While the observed temperatures are far from a conventionally attractive geothermal resource, there are several advantages that make abandoned mines desirable low temperature geothermal resources.

One of the main obstacles to geothermal developments is the high initial capital expenditure and risk associated with drilling wells. If producing from an abandoned mine with a preserved vertical shaft, drilling is not necessary and the total cost of the project is reduced substantially. The savings are project specific, but may be in the range of 40% of the total project cost (ESMAP, 2012).

The numerical simulations indicate that once production begins in a vertical mine shaft, fluid movement rapidly brings warmer water upwards, allowing more heat to be accessed at shallower depths than the geothermal gradient would typically allow. This allows for additional cost savings by reducing the quantity of pipe and pumping power that would be required if extraction was not occurring within mine workings.

Water flows significantly faster through mine workings than through pores or fractures within the undisturbed subsurface, allowing higher volumes of water to be withdrawn from a mine than would be possible in the natural subsurface. This is a particularly important parameter for low temperature resources that rely on heat pump systems.

For Chibougamau and Chapais, having the mines in such close proximity to the towns is a significant advantage. Some of the mines near Chapais have infrastructure beneath the town itself, making them good candidates to provide energy to residential units.

Alternatively, mines several kilometres away are appropriately situated to encourage the development of industrial buildings outside the boundaries of the towns.

This region has demonstrated a willingness to invest in sustainable energy sources. Chapais is home to Quebec's first co-generation biomass power plant, and the Cree community of Oujé-Bougoumou, 20 km further north, heats its infrastructure through a predominantly biomass powered district heating system. Both systems utilize waste products from Chapais' forestry industry (D. Paquette, owner of Plomberie Chibougamau Inc., personal communication, 27 October 2017). Développement Chibougamau, a non-profit focused on the economic development of Chibougamau, was enthusiastic about the prospect of a sustainable energy project in their town.

The next step in progressing towards a geothermal heating system for the region of Chibougamau and Chapais would be to conduct a pumping test in the Copper Rand mine. Real data on the system behaviour would allow the model to be calibrated and increase the reliability of the results. The current results can be seen as a first step that indicates a thermal output of the system on the order of 10^8 MJ, but to provide a more accurate estimate, field observations are needed. While the amount of energy consumed per household is variable, 10^8 MJ may have the capacity to heat over 1600 houses (Manitoba Hydro, 2018).

The scenarios that were simulated with this preliminary model were simple in nature. There are numerous ways the system could be modified to satisfy the needs of a particular system. For example, the costs could be brought down by producing from and injected into the same mine if the energetic requirements are low. Alternatively, if a higher output is required, additional simulations indicated that the sustainable production rate could be significantly increased by adding more than one reinjection site. Furthermore, the heating needs of the community change seasonally, so the installation of a pump capable of handling variable flow rates (reduced in summer and increased in winter) may allow for a higher maximum thermal power output during the highest demand period.

The costs associated with such a system vary substantially depending on the required specifications. A preliminary economic study for numerous potential setups would be possible once the sustainable pumping rate is better constrained. This study would allow for an evaluation of how this source of energy compares to alternative heat sources, to determine if it is cost effective for the region. If the results are favourable, a reliable and environmentally friendly energy source could be the catalyst required to attract industry and investment to the dwindling towns of Chibougamau and Chapais.

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