Modeling potential impact of geothermal energy extraction from the 1B Hydraulic System of the Sydney Coalfield, Nova Scotia, Canada

Jessica MacSween, Chandra Raman, Rajendran Kaliaperumal, Ken Oakes, Martin Mkandawire

Verschuren Centre for Sustainability in Energy and the Environment, Cape Breton University, P.O. Box 5300, 1250 Grand Lake Road, Sydney, Nova Scotia, Canada B1P 6L2, Jessica_MacSween@cbu.ca

Abstract To predict the hydrogeochemical stability of the 1B Hydraulic System of the Sydney Coalfield in Nova Scotia, we are simulating the behavior of groundwater flow and pollution transport using FEFLOW. In order to utilize mine water for geothermal energy extraction, predicating alterations in thermal dynamics is of concern. The simulation considered effects of pumping water from a lower depth and re-injecting into higher depths as well as the change in temperature of the water after energy extraction. This paper presents our preliminary results simulating the potential impact of the geothermal energy extraction on the behavior of groundwater flow and pollution transport.

Keywords groundwater, FEFLOW, finite element analysis, 3D Models, coal seams, geothermal extraction

Introduction

Geothermal energy extraction from mine water is a strategy that makes mine water management economically appealing. In conventional geothermal systems, natural heat from the Earth is extracted to generate electricity and heat buildings; in this case the mine water is used as the heat source. The efficient use of this natural resource can turn mine water management from a burden to an economic opportunity. Consequently, this strategy is among others that is being advocated in the management of the massive mine water legacy left by coal mining that spans close to four centuries in the Sydney Coalfield of Cape Breton, Nova Scotia (Shea 2009). When mining ceased in 2001, the flooding process began and over time the interconnected collieries filled with mine water. In order to counteract this, the upper areas of the major mine pool, the 1B Hydraulic System, are controlled -18 ft (-5.49 m) below sea level (Shea 2008). The 1B Hydraulic System contains 76.7 Mm^3 of water, making it the single largest mine pool within Cape Breton (Shea 2009). The mine water has been geothermally warmed overtime through contact with the rock strata causing the temperature of the water to increase, leaving a high potential for geothermal heat extraction.

Therefore, a geothermal project has been initiated at the 1B Hydraulic System, utilizing the 10 inter-connected and abandoned collieries located in 3 different coal seams. The project will use mine water as a geothermal energy source to provide heating in the winter and cooling in the summer to a senior citizens complex located in New Aberdeen, Glace Bay. The mine workings involved are those of the No. 2 colliery (extraction well) which worked the Phalen Seam between 1899 and 1949 and the No. 9 colliery (injection well) which worked the Harbour Seam between 1899 and 1924 (Shea 2009). The geothermal system in place is an open loop in which the mine water from the No. 2 colliery is pumped from a 253 m deep well into a building, where it runs through a heat pump that either removes or adds heat, it is then injected into a 124 m deep well that is aligned with a depillared area of the No. 9 colliery located 43 m away (Fig. 1). The effects of

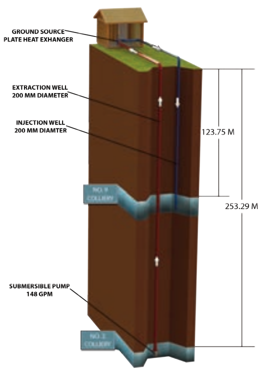

Fig. 1 *Open- loop geothermal system showing the extraction well into the No. 2 colliery and injection well into the No. 9 colliery.*

differences in well depths and change in temperature of the water after energy extraction on the behavior of groundwater flow and pollution transport is unknown.

In light of this, a numerical heat-transport model has been initiated at Cape Breton University using FEFLOW® (Finite Element subsurface FLOW system) developed by DHI-WASY GmbH. The FEFLOW model simulates three-dimensional groundwater flows using finite-element techniques and contamination concentration trends. For our simulation, the model domain is divided into approximately 5000 nodes, creating cells in each layer and covering 20 km^2 of the 1B Hydraulic System. Hypothetical temperature changes and pumping rates based on the capacity of the heat exchanger were utilized. This paper presents our preliminary results simulating the potential impact of the geothermal energy extraction within the 1B System. The flow and pollution transport between these two collieries was not taken into account during this simulation.

Geography and geology of study area

The modeled study area delimits the mine waters of the 1B Hydraulic System, located beneath the communities of Glace Bay, Reserve Mines and Dominion in eastern Cape Breton. The 1B System is one of the three major mine pools within the Sydney Coalfield, consisting of ten abandoned and interconnected underground collieries (No. 1A, No. 1B, No. 2, No. 5, No. 9, No. 10, No. 20, No. 26, Lingan, and Phalen). The No. 1A, No. 5, and No. 10 collieries do not extend under the ocean, while No. 1B, No. 20, No. 26, Lingan and Phalen are entirely submarine. The No.2 and No.9 collieries straddle both the land and the submarine environments. This preliminary study will examine the potential influence of establishing geothermal energy extraction operations at the No.2 colliery, as well as the effect on the No. 9 colliery of which the geothermally extracted water will be injected. Additional collieries situated in the 1B Hydraulic System will be included as the work progresses.

The 1B Hydraulic System was formed following the cessation of mining activities within the Glace Bay Syncline and along the northward flanks of the Bridgeport Anticline (Shea 2009). The mining occurred within the three major coal seams (Emery, Phalen, and Harbour), each occurring at different depths, with Emery being the deepest and Harbour the shallowest (Shea 2008). The coal strata are of Carboniferous age, with the seams separated by sequences of sedimentary material with inter-seam strata generally consisting of mudstone, shale, siltstone, sandstone, and minor carbonaceous limestone (Shea 2009). Probably the inter-seam strata are the result of deposition activity which occurred within fluvial as well as lacustrine environments (Shea 2009).

Mine Connections

The collieries associated with this geothermal project are Nos. 2, 9 and 20 which are part of the larger 1B Mine Pool (1B Hydraulic System). The collieries are located in the New Aberdeen district in the community of Glace Bay. No. 9 colliery was opened in 1899 and was accessed by three deep (approximately 125 m) shafts sunk to the Harbour Seam. That same year, No. 2 Colliery was developed by extending two of the former No. 9 Colliery shafts, and later a third in 1946, down 135 m to the Phalen Seam. In 1939, No. 20 colliery was developed by driving two cross measures tunnels from No. 2 Colliery to the Harbour Seam to access the coal that lay down the dip of No. 9 Colliery (Frost 1962). No. 2 Colliery closed in 1949, however, No. 20 remained open until 1971. During the operation of No. 20 Colliery, No. 9 Colliery had to be kept dry through pumping to avoid overflow into the No. 2, which was directly connected to No. 20. In 1965, to avoid having to maintain No. 9 Colliery, cross measure borehole B-133 was drilled which allowed No. 9 Colliery water to drain into No. 2 Colliery where the water from both collieries was collected and pumped to surface. When No. 20 Colliery ceased operation and pumping terminated, flooding of these collieries began, starting with No. 20, then No. 2 and finally No. 9 Colliery.

The current understanding is that these 3 collieries are hydraulically connected to each other by this main borehole connection (B-133) and it is assumed that the borehole is open. In addition, the collieries could be hydraulically connected through their shafts, however, the connections are likely weak because the shafts were backfilled . The method of water flow through these collieries is not well understood and more time is needed to comprehensively analyze the mine workings and potential hydraulic connections so that they can be included in the model. For this preliminary study, only No. 2 and No. 9 Collieries have been taken into account.

No. 9, No. 2 and No. 20 Collieries are connected to the 1B Mine Pool of the Sydney Coalfield however the connection is not well known. The 1B Mine Pool water is kept at -5.5 metres below sea level by pumping at Neville Street Wellfield (Shea 2008, 2009). In 2010, a drilling program investigated the mine waters of No. 2 and No. 9 Collieries and the average mine water elevation for the collieries over a 2 month period (CRA 2010) was measured as -8.87 and -4.47 metres respectively. Because of the different hydraulic heads, it is suspected that the mine water in these two collieries is not significantly influenced by the pumping at Neville Street Wellfield. There is a tunnel connection between No. 2 and No. 1B Colliery to the west however, this connection is documented to be blocked by a constructed dam, though the current theory suggests there is probably some leakage around the outside of the dam.

Modeling and simulation conditions

The geometry of the model was created using the mine maps of the No. 9 and No. 2 collieries (Fig. 2). Thereon a super mesh was created that contained a definition of the outer model boundary, followed by the creation of the finite element mesh. Subsequently, the model was extended into three dimensions (3D) with the 3D layer configuration adjusted so the layers corresponded to actual layers found underneath the study area, including the Harbour and Phalen Seams. Four layers were selected which automatically lead to five slices. The thickness of the layers was obtained from ECBC 2010 Drilling Program. The thickness of the layers is as follows: 121.31 m for the first rock layer, 2.13 m for the Harbour Seam, 129.85 m for the subsequent rock layers and 2.20 m for the Phalen Seam. The data regionalization was done using Akima interpolation procedure. The model has approximately 7000 triangular prismatic elements and approximately 5000 nodes.

The flow simulation was set as a standard saturated groundwater flow equation based on Darcy's model with the state set as transient. For this simulation, the boundaries of the model are confined within the No. 2 and No.9 collieries, therefore, no flow is assumed between these collieries and the nearby collieries of the 1B mine pool. Two wells, B-218 (injection) and B-219 (extraction), will be used in this model for the geothermal heat exchange. For these two multi-layer wells, several parameters were assigned. The well radius was set as 0.10 m and top elevations were set at 19.52 and 19.42 m while bottom elevations were set at -237.13 and -104.33 m for wells B-219 and B-218, respectively. The state of the thermal energy transport was set to transient and a time series

Fig. 2 *Model area – The area encompasses the No. 9 and the No. 2 collieries of the 1B Hydraulic System of the Sydney Coalfield, Cape Breton, Nova Scotia (during the interlaying, part of the No. 2 colliery has been blanked out).*

with linear interpolation was set for the wells detailing the hypothetical pumping rates throughout the year.

Next several parameters for the hydraulic flow were set. The groundwater recharge data was obtained from the Environment of Canada National Climate Data and Information Archive for Sydney A from 1999–2013 and is 1492.2 mm/a. The hydraulic conductivity was approximated using lithological data from Conestoga-Rovers and Associates (2010) and Baechler (1986). The first and third layers in the model represent the layers of rock above and below the coal seams in question. This area contains about 140 m of siltstones and sandstones, with interbedded mudstones, shale, occasional limestones, and two thin coal seams (Cain *et al.* 1994). Therefore, a hydraulic conductivity average was created for these layers using the hydrostratigraphic unit for siltstone and sandstone. The lower range values are 4.2×10^{-7} and 1.0×10^{-5} cm/s for siltstone and sandstone respectively (Bachelor 1986), the mean value of 5.2×10^{-5} cm/s was used as the hydraulic conductivity. The conductivity of the subsequent layers was set at 8.2×10^{-5} cm/s for the Harbour and Phalen Coal Seams. The values obtained from Baechler (1986) state that the coal seams of the Upper Morien range from 1.6×10^{-5} to 4.1×10^{-7} cm/s. For this study, the mean value was used as the hydraulic conductivity for the Harbour and Phalen Seams. The author acknowledges that these values will vary over the landscape and are not constant values; the averages are used for the preliminary study until more information can be pooled to get a comprehensive portrayal of the lithology.

Lastly, the open loop system was incorporated into the model. Open loops systems are treated as multi-layer wells in FEFLOW, containing both injection and extraction wells. The initial temperature of the model was set to 15.7 °C, which is the temperature of the extraction well recorded by ECBC 2010 Drilling Program. A time series with linear interpolation for the open loop was also set and the nodes belonging to the injection/pumping nodes were assigned a value equal to the number of the time-varying power function which contains the corresponding temperature differential for the model. The temperature differential for the model utilizes Δ T +3 K for heating and -3 K for cooling. The varying pumping/infiltration rate is based on a similar demand model and includes the maximum pumping capacity of 148 US.liq.gal/min (560 L/min) indicated in the heat schematics of the proposed system. In each time step, the module will calculate the average extraction temperature and averaging will be based on the contribution to total energy extraction by pumping from each extraction node (DHI-WASY Support, personal communication April 19th, 2013).

3D Heat Transport Model

The temperature difference between the extraction and injection wells can be seen in Fig. 3. The result of the simulation shows that the temperature at the point of injection after 7300 days is 10.2 °C, while the extraction temperature is 13.2 °C. This verifies that the system is working properly as the average temperature over the course of 7300 days shows the prescribed temperature differential between the inlet and outlet of 3 °C. The Fig. depicts a heating period with a maximum pumping rate 806.7 m^3/d.

The final Fig. displays the injection and extraction temperatures over the period of 7300 days (Fig. 4). The injection temperature appears to be stable throughout the time period, as well as the extraction temperature. However, there is a slight decrease in the extraction temperature over the course of 7300 days. Most notably, at 4205 days where the temperature changes to 13.9 °C and at 7262 days it changes further to 12.9 °C. This is a possible indication of a short circuit situation which could affect the longevity of the system. In addition, it should be noted that the two wells are located at 43 m away from each other. The wells have different extraction and injection points, separated by approximately 130 m of rock strata. However, the cooling of the geothermal reservoir is a possibility and should not be overlooked during production. For this preliminary study, however, due to the fact that the connections of the two mines were not taken into account this result is not conclusive and requires further investigation.

Discussion

The preliminary results suggest the impact of a geothermal energy extraction scheme on mine water temperature is dependent on many variables, those of which have yet to be interpreted. The modeled scenarios did not take into account the important connections between these two collieries, namely the main connection borehole B-133 that connects the

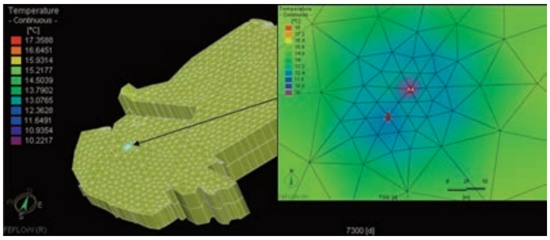

Fig. 3 *3D model of the temperature differences between the injection and extraction wells at the final time series of 7300 days.*

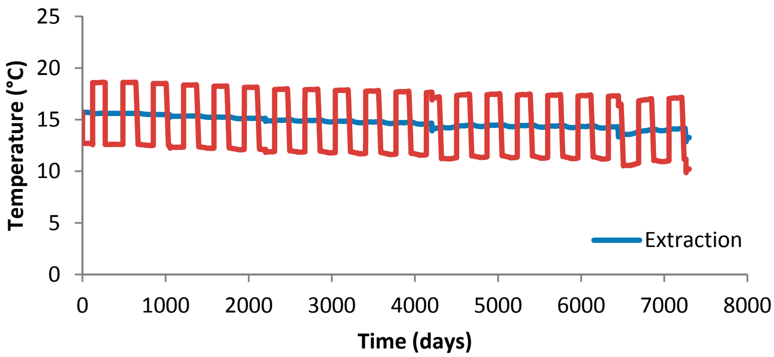

***Fig. 4** Extraction and injection temperature results showing the oscillations of the temperature differential, as well as the slight decrease in the extraction temperature.*

No. 9 and No. 2 collieries. However, this model is a step in the right direction. Further investigations are needed to properly calibrate and take into account the mine workings, so that a predicted flow regime can be applied to the model.

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References

Baechler FE (1986) Regional Water Resources Sydney Coalfield, Nova Scotia. Province of Nova Scotia: Department of the Environment.

Cain P, Forrester DJ, Cooper R (1996) Water Inflows at Phalen Colliery in the Sydney Coalfield and their Relation to Interaction of Workings. In International Mine Water Proceedings, Nottingham, U.K., p 83–95.

Conestoga-Rovers and Associates (CRA) (2010) ECBC Drilling Program Investigate Mine Water at No. 2 and No. 9 Collieries, Glace Bay, Cape Breton County, Nova Scotia. Ref No. 059546.

Frost L (1962) The Louis Frost Notes 1685 to 1962. Retrieved June 13, 2013 from www.mininghistory.ns.ca/lfrost/lfdn2.htm.

Shea J (2008) Innovative Mine Water Management Techniques for Submarine Coal Mines of the Sydney Coalfield, Nova Scotia. Presented at West Virginia Mine Drainage Task Force Symposium, Morgantown, West Virginia, April 22, 2008.

Shea J (2009) Mine Water Management of Flooded Coal Mines in the Sydney Coal Fields, Nova Scotia, Canada. In: International Mine Water Proceedings, Pretoria, South Africa, p 289–297.