Hydrogeological Modeling of Mining Operations at the Diavik Diamonds Project

Ken Kuchling, P.Eng
Diavik Diamond Mines Inc., Calgary Alberta Canada

Don Chorley, P.Geo
Golder Associates Ltd. Vancouver, British Columbia, Canada

Willy Zawadzki
Golder Associates Ltd. Vancouver, British Columbia, Canada

ABSTRACT: Diavik Diamond Mines Inc. proposes to develop a diamond mining project at Lac de Gras in the Northwest Territories. As part of the Environmental Assessment, and mine design, estimates of mine water inflow quantity and quality were required. This paper describes the field investigations and numerical modelling studies that were completed in order to evaluate the groundwater conditions at site. The Diavik Diamonds Project is located in the Canadian Shield within the region of continuous permafrost, however mining operations will be located in unfrozen ground within the confines of a diked-off portion of Lac de Gras. Field investigations used to characterise the hydrogeological regime at site consist of extensive packer testing supplemented with a limited program of borehole flowmeter testing, borehole temperature logging and borehole camera imaging. This information was used to develop a conceptual hydrogeological model for the site, which in turn was modelled numerically using MODFLOW and MT3DMS to predict groundwater inflow volumes and water quality with time. Results indicate that the total mine inflows are expected to range up to 9,600 m^3/day with TDS concentrations gradually increasing in time to maximum levels of about 440 mg/L. The modelling also showed that lake water circulating through the rock mass will eventually comprise more than 80% of the mine water handled.

1 INTRODUCTION

The Diavik Diamonds Project is located at Lac de Gras, 300 kilometres northeast of Yellowknife, N.W.T, shown in Figure 1. The project is a joint venture between two Canadian companies, Aber Resources Ltd. (40%) of Toronto and Diavik Diamond Mines Inc. (60%) of Yellowknife, a subsidiary of Rio Tinto plc of London, England.

The project will entail the mining of four diamondiferous kimberlite pipes, termed the A154S, A154N, A418, and A21 pipes. The total kimberlite resource stands at about 37 million tonnes with an average grade of 3.6 carats per tonne, for a total resource of about 133 million carats. The proposed mine plan consists of the initial development of three open pit mines after which underground mining operations will continue beneath two of the pits (A418 and A154 pits). The estimated mineable ore reserve is approximately 26 million tonnes yielding an estimated 102 million carats over the 20 year mine life. Twenty million tonnes of the reserve will be mined with open pit methods while the remaining 6 million tonnes will be recovered with underground methods. Mining operations will extend to a depth of 400 metres below the lake bottom.

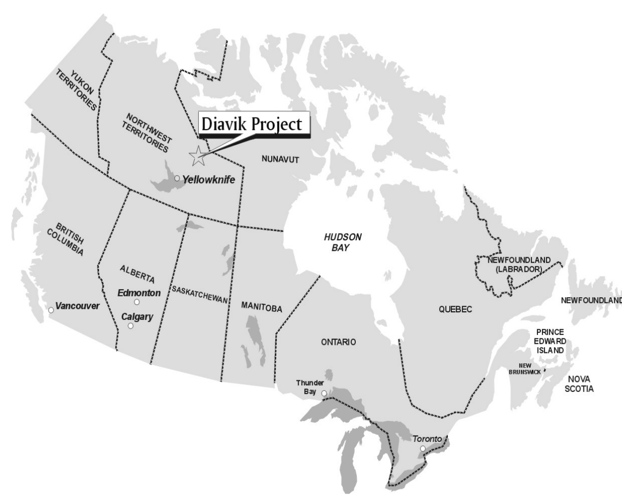

Figure 1: Project Location

The Diavik project is located within the region of continuous permafrost, about 250 kilometres south of the Arctic Circle. The four kimberlite pipes are all located within the footprint of Lac de Gras, approximately 100 to 800 metres from the shoreline of east island. Therefore unfrozen ground conditions will be encountered in all the pits during mining.

Water retention dikes will be used to isolate the pit areas from the lake (Figure 2) with the consequence that groundwater will flow through the unfrozen rock. A key part of the project environmental assessment and mine design was prediction of the quantity and quality of mine water. The focus of this paper is on the hydrogeology of the A418 and A154 pit areas (Figure 2).

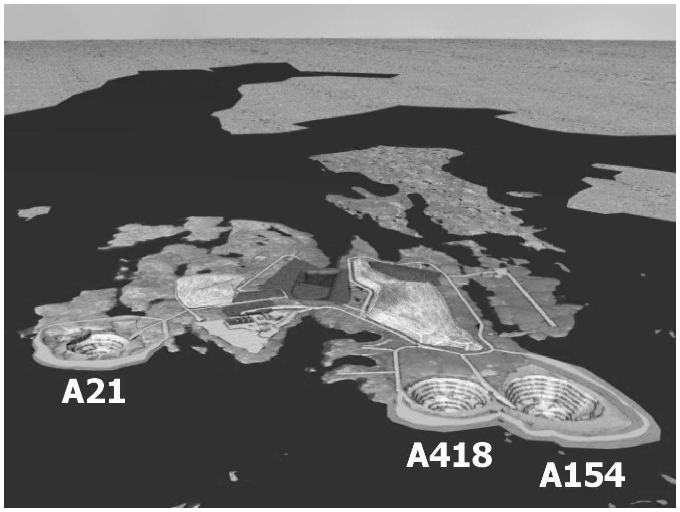

Figure 2: Project layout

2 GEOLOGICAL SETTING AND PERMAFROST CONDITIONS

The regional geologic setting for the Lac de Gras area is within syntectonic and post-tectonic intrusive rocks of the Slave Province. The main Archean rock units consist of sedimentary greywacke metaturbidites, biotite tonalite, 2-mica granite, and granodiorite. Proterozoic diabase dike swarms also appear regionally. The open pits will be developed in competent granitic country rocks with Rock Quality Designation (RQD) in the range of 95%. Existing fractures and local joint systems will therefore govern the hydrogeology of the country rock mass.

The formation of the kimberlite pipes are relatively recent geological events, having been emplaced approximately 50-60 million years ago. For comparison, the host rocks vary from 2.5 to 2.7 billion years in age and the younger diabase dikes at 1.3 to 2.6 billion years in age. The kimberlite pipes are cylindrically shaped and near vertical, with diameters of about 80-120 metres.

The pit areas are overlain with approximately 10 metres of overburden, consisting of an average of eight (8) metres of bouldery till and two (2) metres of lake bed sediments. The upper few metres of the bedrock can be weathered with some open joints being infilled with silty fines.

Permafrost develops in areas where the heat loss from the ground during winter exceeds the combined energy gain during the summer and energy radiated by the local geothermal gradient (i.e. heat radiating upwards from depth). Permafrost generally develops under dry land masses where the ground surface is exposed to prolonged cold air temperatures. The average annual air temperature at the Diavik site is –12ºC. Beneath bodies of water which do not entirely freeze to depth (>1.5 metres deep at the Diavik site), taliks, or thawed zones, will be present. In these locations, the lake water and lakebed will only cool to temperatures in the range of 0ºC to +1ºC in winter and this relatively "warm" temperature will prevent the development of permafrost in the ground. At the Diavik site the permafrost depth has been measured to a vertical depth of about 380 metres below the east island and the ground temperatures are typically in the range of -5ºC. Permafrost depths measured under the various small islands in the lake range from 100 metres to being non-existent, depending on the size of the island. Along the lake shoreline, permafrost has been shown to extend sub-vertically downwards from the lake edge contact forming a "bulb" shaped zone under the islands. Hydrogeologically, permafrost is considered to be impervious.

3 HYDROGEOLOGICAL INVESTIGATIONS

In order to characterize the hydrogeology of the site, three successive geotechnical/hydrogeological field programs were conducted between the years 1996 and 1998. The locations of these boreholes are shown in Figure 3.

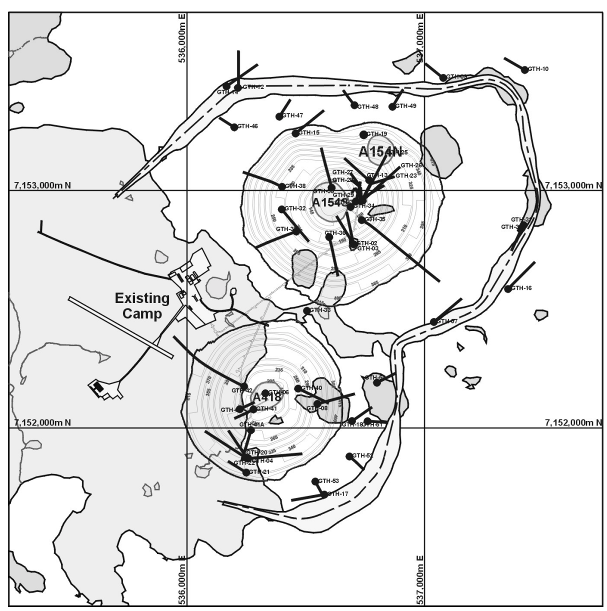

Figure 3: Geotechnical Borehole Locations

On average they were drilled at inclinations of –55º to vertical depths of 245 metres although two holes were extended down to 600 metres. Since the pit areas are under the lake, drilling was from the ice and restricted to the winter seasons only (February to mid-April). These core holes were logged geotechnically, including the collection of oriented core data. Packer testing was also undertaken in these holes. The goal of the hydrogeological investigations were to assess the hydraulic conductivity of the rock mass as a whole, and to determine the major factors controlling water flow, i.e. are the main flow paths along the natural jointing in the rock or mainly along major structures such as broken zones or faults. Knowledge of the groundwater flow system would help develop the conceptual hydrogeological model and aid in design of water collection or mitigation measures if needed. A 1000-metre long bulk sample decline was excavated to the A154S pipe (Figure 3) and this development also provided opportunity to assess hydrogeological conditions on a somewhat larger scale, although only 600 metres of the decline was actually in unfrozen rock beneath the lake. The length could be extended to 800 metres if boreholes drilled out from the face are included.

Four types of hydrogeological field investigation methods were used at site. They consisted of; (i) packer testing, (ii) borehole flowmeter testing, (iii) borehole temperature logging, and (iv) borehole video imaging.

Packer testing: Approximately two hundred shallow and deep HQ and NQ sized core holes were drilled as part of the geotechnical and hydrogeological investigations for the pit walls and the water retention dikes (pit wall holes only are shown in Figure 3). Most of the geotechnical holes were packer tested using constant head tests although some falling head tests were also conducted. In total approximately 600 packer tests were completed in the country rock over packer intervals ranging from 40 metres down to 3 metres. Packer testing intervals associated with the water retention dike design were generally short, in the range of 3 to 10 metres in both the bedrock and overburden. Packer tests associated with the pit investigations were done over 40 metre intervals in the bedrock only. The deepest packer test at site was done at a vertical depth of 570 metres below lake bottom.

Heat pulse flowmeter logging: This geophysical technique utilizes a down-the-hole probe that can measure water flow rates along a borehole. A small diameter submersible pump is used to lower the head in the borehole in order to induce upward water flow from depth. The flowmeter tool is lowered to various locations in the hole in order to take flow rate measurements. As cumulative flows are measured at various points in the hole, water-bearing zones can be identified by changes in borehole flow quantity. The water-bearing zone would be somewhere between a "high flow" reading and the previous "low flow" reading. Several boreholes were tested with this method however only one provided good results. In the unsuccessful holes, extremely permeable zones near the top of the hole yielded almost all of the water influx and consequently very little upward flow could be induced. Figure 4 shows a typical plot from the flowmeter log. The maximum and minimum values were determined by taking several readings at each depth increment.

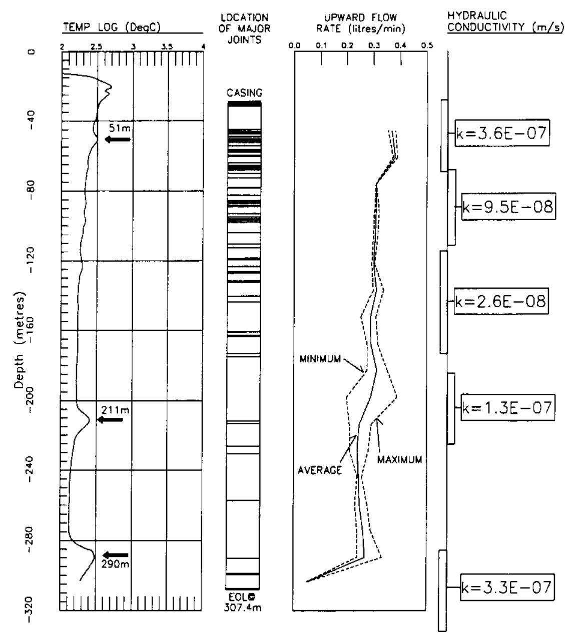

Figure 4: Example borehole geophysical log

Resistivity/temperature logging: This geophysical technique also utilizes a down-the-hole probe that measures both water temperature and fluid resistivity. Changes in water temperature along the borehole are signs of natural seepage or diffusion of groundwater into the hole. No flow is induced in the hole for this test in order to prevent mixing of water and the smearing of temperature signatures. The geophysical probe is lowered down the hole at a constant rate of about three metres per minute with a reading automatically taken every 3-cm. Due to the low Total Dissolved Solids (TDS) in the lake water and groundwater at the site, resistivity values were too low to be measured and therefore did not provide any useful information. Temperature readings generally measured borehole fluid temperatures of between

2ºC to 3ºC, with the water bearing zones showing a slight temperature increase, in the range of 0.1ºC to 0.5ºC. Figure 4 shows a typical plot of a temperature log. Four boreholes were tested with this tool.

Borehole video imaging: This technique utilizes a SeeSnake down-the-hole camera. The self-illuminating camera provided black and white images along hole lengths in the range of 300 metres. After a 3 to 6 hour hole flushing period, the camera was lowered down the hole at a rate of about three metres per minute. Elapsed time and depth along hole are tracked with a pulley wheel equipped with an encoder and are displayed on the video image and recorded on videotape. At 300 metres the depth accuracy was usually to within 40 cm and was never off more than 70 cm. Five holes were examined with the camera. The goal of the video imaging was to examine water bearing zones identified by the packer tests and temperature logs. This was to determine whether the flow was from a highly broken zone or from an area with widely spaced single fractures. The images also helped to compare the in-situ rock mass with geotechnical core logs. It became apparent that in some instances, broken zones in the core appeared in-situ as tight fractures. Conversely several single fractures were encountered with centimeter wide joint apertures, something that would not be determined by examining core.

4 HYDROGEOLOGICAL CHARACTERIZATION

For hydrogeological characterization purposes, the country rock at Diavik was initially considered to consist of two domains, fractured rock zones and weakly fractured rocks, that can be differentiated based on the frequency, spacing and connectivity of the fractures. This differentiation is similar to the approach used by researchers at the Whiteshell Research Area (Stevenson et. al., 1996). A fractured rock zone was defined as a zone with enhanced fracture density and permeability relative to the background, that is spatially continuous over the scale of hundreds of metres or more. These zones are significant hydrogeological features that are important to groundwater flow because of their size, hydraulic conductivity, and connectivity. A zone of broken rock that is not significantly permeable due to sealing or a limited lateral extent would not be classified as a fractured rock zone. Highly permeable single fractures, on an individual basis, are not considered to be significant hydrogeological features, as they are not expected to extend over such large distances. Weakly fractured rock is defined as a volume of rock that contains relatively infrequent open fractured that are generally poorly connected. Weakly fractured rock is, on average, significantly less permeable than the fractured rock zones. By comparing the drill core logs and core photographs with packer tests and geophysical data, it was readily apparent the some of the highly permeable zones in the rock mass consisted of open, single joints. Broken rock zones identified in the core were not necessarily significantly water bearing. Possibly the broken zones consisted of random joints that happen to be closely spaced rather than being associated with a major fault structure. In fact very few fault zones were ever identified in the drill core or during construction of the bulk sample decline. Major water inflows encountered in the decline were mainly associated with single open joints. Figure 5 is a photo of a 1-cm wide vertical open joint that was encountered in cover drill hole in the decline. This joint was by far the most significant water bearing structure intercepted over the 600-metre decline length and resulted in temporary flooding at the decline face. Grouting eventually sealed off the uncontrolled water flow (grout can be seen in the lower portion of the fracture). Most of the rock domain at Diavik is therefore comprised of weakly fractured rock. Fractured rock zones appear to be rare and widely spaced.

Figure 5: In-situ open fracture

From a hydrogeological modeling perspective, the conclusions from the field investigations confirmed that the most reasonable approach would be to model the rock mass as a single hydrostratigraphic unit using an average hydraulic conductivity rather than try to interpret distinct major water bearing horizons within the country rock. The next step in the hydrogeological characterization was to determine the average hydraulic conductivity and evaluate spatial trends in the data.

Figure 6 provides a histogram of the hydraulic conductivity (K) data derived from packer tests in the granitic country rock. The data appears to follow a lognormal distribution and range over several orders of magnitude, from 10^{-3} m/s to 10^{-9}m/s, with a mean of 2x10-7 m/s. Table 1 provides a summary of the measured hydrogeological parameters in the various stratigraphic units.

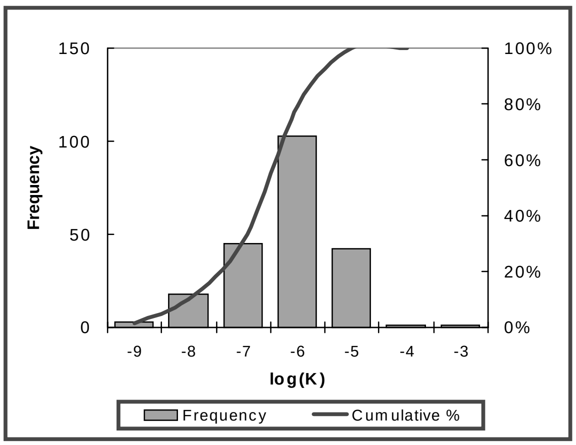

Figure 6: Packer test results

Researchers have shown that at various sites in the Canadian Shield and at other locations worldwide, rock mass permeability decreases with increasing depth. (Davison et al., 1994 a & b; Stevenson et al., 1996 a & b; Ophori et al., 1994 & 1996; Raven et al., 1987; and Burgess, 1979).

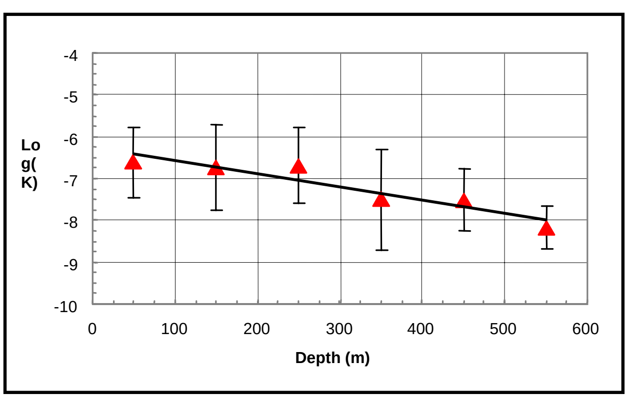

Figure 7: Hydraulic conductivity with depth

In order to assess whether there is a similar depth dependent trend at the Diavik site, average K values were calculated for successive 100 metre vertical intervals. The results are shown in Figure 7. The error bars show the maximum and minimum values over that interval. A general trend of decreasing K with depth is apparent in the data.

Table 1: Hydraulic Conductivity (K) Summary

Hydrogeological Unit	**Average Measured K Values**	**Calibrated K**
Lakebed sediments & till	4 x 10^{-5} m/s	*Not modeled*
Country Rock	2 x 10^{-7} m/s	5 x 10^{-7} m/s
Kimberlite	4 x 10^{-7} m/s	3 x 10^{-6} m/s
Diabase Dike	5 x 10^{-8} m/s	5 x 10^{-8} m/s

Hydraulic conductivity data in the kimberlite was collected mainly from cover holes in the bulk sample. Packer tests were not completed vertically down the kimberlite pipe due to difficulties with borehole collapse. The average K in the kimberlite was measured at 4x10^{-7} m/s.

In the lakebed overburden soils, the range of K values measured was between 7x10^{-3} and 2x10^{-8} m/s, with an average of 4x10^{-5} m/s. Since the K for the overburden soils was greater than that of the underlying bedrock, it would not be a controlling factor in groundwater recharge. Consequently, for simplification purposes, the overburden layer was excluded from the groundwater model.

Typically in the Canadian Shield, the concentration of Total Dissolved Solids (TDS) in the groundwater increases with depth. As part of the environmental baseline study, water quality sampling was conducted in the upper 350 metres of the rock mass at the Diavik site. Attempts to take deeper water samples were unsuccessful. Consequently the site data was supplemented with water quality samples collected at the Echo Bay Lupin Mine at depths in the range of 800-1300 metres. The Lupin Mine is about 100 kilometres north of the Diavik site. The combined water quality results (TDS) are plotted in Figure 8, which also presents water quality results collected by researchers elsewhere in the Canadian Shield. Two TDS versus depth profiles were developed; ① a profile based on the Canadian Shield data, and ② the Diavik profile based on the local and Lupin data. The Diavik profile estimates that at 500 metres depth the TDS concentration is 1000 mg/L and at 1000 metre depth the TDS concentration would be 6,400 mg/L. At 1600 metres the concentration would be 100,000 mg/L. Since mining operations are only planned to a depth of about 400 metres, a significant amount of groundwater upwelling could introduce quantities of high TDS water into the mine, which could affect the environmental impacts of the operation as well as capacity of the project water treatment plant.

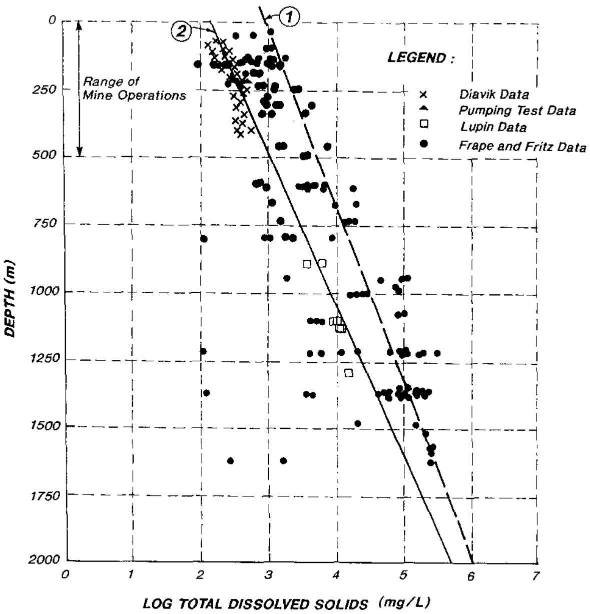

Figure 8: TDS vs. depth profile

5 GROUNDWATER MODELLING

Initially a preliminary modeling study was done to evaluate the type of model that should be used. Due to increasing TDS concentrations with depth it was possible that variable fluid densities could potentially influence the modeling results. A two-dimensional numerical model representing a vertical cross-section through A418 mine was used to compare flow and transport predictions that included variable density with predictions based on constant density. The model was constructed using FEFLOW (Diersch, 1998), which is a finite element code capable of simulating density and viscosity coupled groundwater flow, transport of solutes, and heat flow in three-dimensional porous media under a variety of boundary conditions. Due to the relatively low TDS concentrations and because of the relatively high hydraulic gradients that will be induced by mining, density effects were deemed to be negligible. Consequently the decision was made to use a single fluid density approach.

A detailed three-dimensional flow and transport model was constructed using Visual ModflowTM (Waterloo Hydrogeologic, 1999), which is a graphical pre- and post-processor for MODFLOW and MT3DMS model codes. MODFLOW is a finite difference code that was developed by the United States Geological Survey (McDonald and Harbaugh, 1988) to simulate transient groundwater in three-dimensional porous medium. MT3DMS is a MODFLOW companion code developed for the United States Environmental Protection Agency ((Zheng and Wang, 1998) which is capable of simulating three-dimensional, transient transport of dissolved chemicals in groundwater, using the grid and hydraulic heads calculated by MODFLOW. Both models assume that changes in the densities of a solute have insignificant effects on groundwater flow and solute transport.

The MODFLOW model grid for the A418/A154 pit area, shown in Figure 9, encompassed an area of 4.8 km by 5.3 km to a depth of about 1500 metres. It consisted of 108 columns, 125 rows, and 26 layers for a total of approximately 350,000 grid blocks. To provide sufficient resolution for model predictions and to ensure the stability of numerical solution, the grid block size is about 30 meters in the vicinity of the mines and increases towards the model boundaries. A separate, similar sized model was created for the A21 pit area.

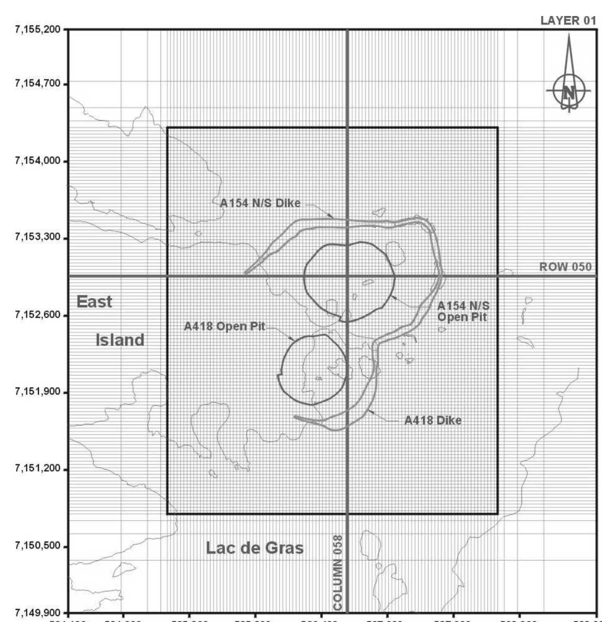

Figure 9: MODFLOW grid layout

Model calibration was completed by comparing actual inflows measured in cover holes drilled ahead of the bulk sample decline with inflows predicted by the model. The model could not be calibrated to the total water inflow recorded in the decline since grouting was regularly used to control inflows. The calibration process resulted in some minor changes to the initial hydrogeological parameters. Calibrated parameters are summarized in Table 1.

The groundwater model simulated the project development sequence, including construction of the water retention dikes and the staged excavation of the open pits and underground mines. Changes in the extent of mine components were incorporated in the model by automatically adjusting model boundaries every two years during the twenty-year mine life.

The predicted A418/A154 groundwater inflow quantities are shown in Figure 10, illustrating how inflow quantities increase with time as the pits and underground mines are deepened. The plot also shows corresponding TDS concentration in the mine water. Due to the lower permeability at depth, the amount of deep-seated brackish groundwater welling up is relatively minor. The TDS concentrations are averaged over the entire mine, combining lower TDS water from the upper portions of the pit with higher TDS water ingress near the pit bottom. The peak groundwater flows into the A154 and A418 open pit and underground workings is about 9,600 m^3/day with an average TDS concentration of 440 mg/L.

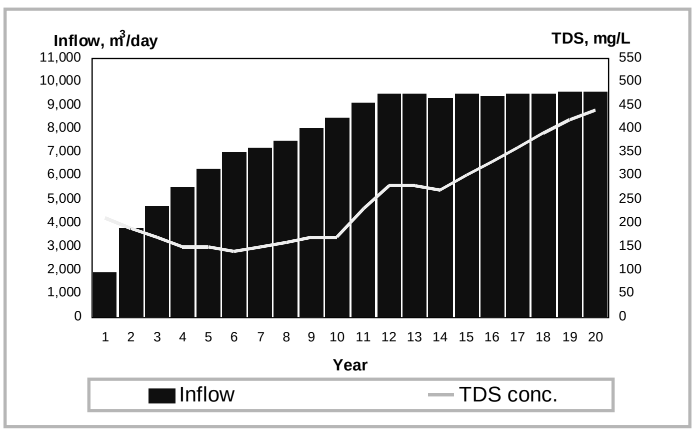

Figure 10: Mine inflow quantity and TDS concentration

Figures 11 and 12 provide MODFLOW cross-sections through the A418/A154 pit areas showing hydraulic head and TDS concentration contours at Year 10 and Year 20 of the mine life.

In order to observe to what extent lake water migrates into the pit, an MT3D model run was done whereby the groundwater TDS concentrations were set to 0 mg/L and the lake water was arbitrarily set to 100 mg/L. By determining the mine inflow water quality with time, one is able to see how the percent lake water reporting to the pit increases with time. Figure 13 shows that the contribution of lake water to the total mine inflow increases rapidly in the first 5 years, and then levels off at about 85%

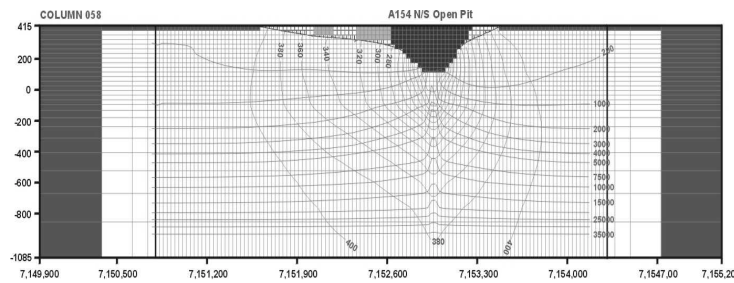

Figure 11: Hydraulic heads at Year 10

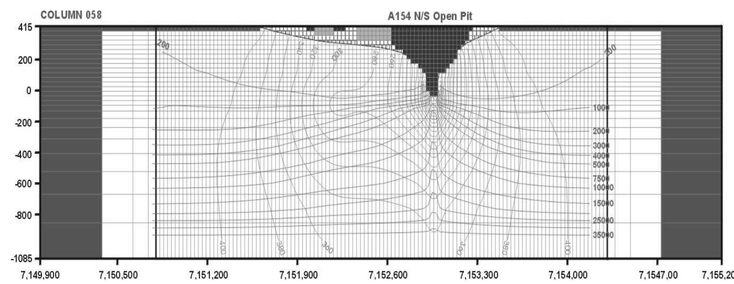

Figure 12: Hydraulic heads at Year 20

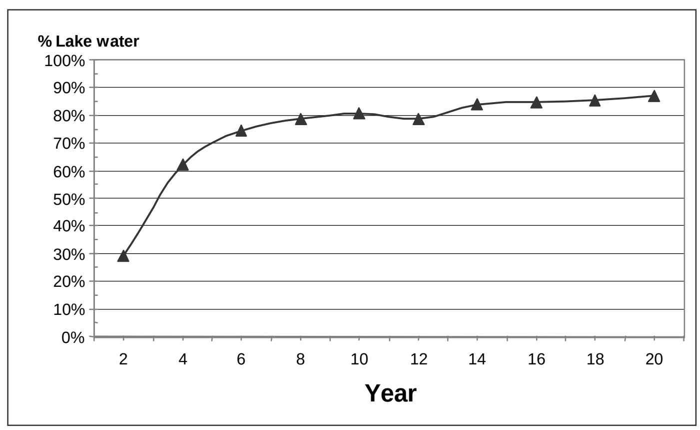

Figure 13: Percent lake water infiltration

6 CONCLUSIONS

Based on the hydrogeological investigations conducted at the Diavik site, it is reasonable to model the large scale rock mass as a single, hydrostratigraphic. A single fluid density approach is also valid even though the groundwater exhibits increasing TDS concentrations with depth.

Borehole temperature logging provides a relatively quick and simple way to assess the frequency and position of potential water bearing zones.

The current plan is to install a few deep Westbay type water sampling wells at site to monitor for upwelling of groundwater from depth. These will provide water quality data long before actually encountering higher TDS water in the mine workings.

The groundwater model will continue to be used as a predictive tool over the operating life of the mine. The hydraulic regime at site will be closely monitored and on-going model calibration will take place.

7 REFERENCES

Burgess, A.A. 1979. Pluton Hydrogeology. Atomic Energy of Canada, Ltd. TR-73.

Davison, C.C., A. Brown, R.A. Everitt, M. Gascoyne, E.T. Kozak, G.S. Lodha, C.D. Martin, N.M. Soonawala, D.R. Stevenson, G.A. Thorne, and S.H. Whitaker. 1994a. The Disposal of Canada's Nuclear Fuel Waste: Site Screening and Site Evaluation Technology. AECL-10713, Whiteshell Laboratories, Pinawa, Manitoba.

Davison, C.C., Chan, T., Brown, A., Gascoyne, M., Kamineni, D.C., Lodha, G.S., Melnyk, T.W., Nakka, B.W., O'Connor, P.A., Ophori, D.U., Sheier, N.W., Soonawalla, N.M., Stanchell, F.W., Stevenson, D.R., Thorne, G.A., Vandergraaf, T.T., Vilks, P., and Whitaker, S.H. 1994b. The Disposal of Canada's Nuclear Fuel Waste: The Geosphere Model for Postclosure Assessment. AECL-10719, Whiteshell Laboratories, Pinawa, Manitoba.

Diersch, H.G. 1998. FEFLOW Interactive, Graphics-Based Finite-Element Simulation System for Modeling Groundwater Flow, Contaminant Mass and Heat Transport Processes. WASY Institute for Water Resources Planning and System Research Ltd., Berlin, Germany.

Frape, S. K. and Fritz, P. 1997. Geochemical trends for groundwaters from the Canadian Shield; in Saline Water and Gases in Crystalline Rocks. Editors: Fritz, P. and Frape, S. K. Geological Association of Canada Special Paper 33, p. 19-38.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite difference groundwater flow model. Techniques of Water-Resources Investigations, 06-A1, U.S. Geol. Surv., 528 p.

Stevenson, D.R., A. Brown, C.C. Davison, M. Gascoyne, R.G. McGregor, D.U. Ophori, N.W. Scheier, F.W. Stanchell, G.A. Thorne and D.K. Tomsons. 1996a. A Revised Conceptual Hydrogeologic Model of a Crystalline Rock Environment, Whiteshell Research Area, Southeastern Manitoba, Canada. AECL-11331, Whiteshell Laboratories, Pinawa, Manitoba.

Stevenson, D.R., E.T. Kozak, M. Gascoyne and R.A. Broadfoot. 1996b. Hydrogeologic Characteristics of Domains of Sparsely Fractured Rock in the Granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada. AECL-11558, Whiteshell Laboratories, Pinawa, Manitoba.

Ophori, D.U. and T.Chan. 1994. Regional Groundwater Flow in the Atikokan Research Area; Simulation of 18O and 3H Distributions. AECL-11083. Manitoba.

Ophori, D.U., Brown, A., Chan, T., Davison, C.C., Gascoyne, M., Scheier, N.W., Stanchell, F.W., and Stevenson, D.R., 1996. Revised Model of Regional Groundwater Flow in the Whiteshell Research Area. AECL Whiteshell Laboratories, Pinawa, Manitoba.

Waterloo Hydrogeologic Inc. 1999. Users Manual for Visual MODFLOW v. 2.8.1 – The Fully Integrated, Three-Dimensional, Graphical Modeling Environment for Professional Groundwater Flow and Contaminant Transport Modeling. Waterloo Hydrogeologic Inc., Waterloo, ON.

Zheng, C. and P.P. Wang. 1998. MT3DMS, a Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems, Documentation and User's Guide. University of Alabama. prepared for U.S. Army Corps of Engineers.