USE OF A FROZEN-EARTH WALL TO REDUCE EFFECTS OF DEWATERING ON ALLUVIAL AQUIFER IN VICINITY OF THE PROPOSED AQUARIUS OPEN PIT MINE

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Abstract: The Aquarius gold mining project in Timmins, Ontario, Canada, is being developed by Echo Bay Mines (EBM). The mine site is located 1.5 km south of Kettle Lakes Provincial Park in an area characterized by small lakes and streams. The depth to ground water in the mine area is less than 15 m. Mineralization occurs in Precambrian bedrock that is overlain by approximately 100 m of saturated glacial alluvium. The alluvium covering the deposit grades from lacustrine silts and clays on the west side of the proposed mine to esker gravels on the east. The use of perimeter dewatering wells was initially evaluated as a means to control inflow to the proposed open-pit mine and to stabilize the pit highwalls. The analysis indicated a pumping rate of 3,000 L/s during the 8.5 year mine life would be required to dewater the deposit. Infiltration ponds and direct discharge of water to some of the adjacent lakes were reviewed as methods for mitigating changes in water levels. Based on the results of the preliminary dewatering analysis, alternative methods of water control were reviewed to reduce dewatering costs and effects on the regional surface- and ground-water resources. A frozen-earth wall was selected as a means of reducing the dewatering rates and changes to the regional hydrologic system. The use of the frozen-earth wall will reduce the dewatering to less than 700 L/s over a period of three years and also minimize impacts to the regional aquifer system during mining.

Key Words: mine hydrology; dewatering; frozen-earth wall; aquifer; esker; Aquarius Mine

Introduction

The proposed Aquarius open pit gold mine is located approximately 40 km east of the center of Timmins, Ontario, Canada and approximately 1.5 km south of Kettle Lakes Provincial Park (Figure 1). The Aquarius gold deposit had previously been worked underground by Asarco Exploration Company of Canada Ltd. In 1995, EBM acquired the property, and subsequently defined a surface-mineable gold reserve. EBM commissioned a hydrologic investigation to design an effective dewatering system for the mine, and to assess the potential impacts of the proposed mining, associated dewatering, mine-water disposal, and pit-lake infilling on the water resources of the region. Of particular concern were the lakes within the Kettle Lakes Provincial Park.

Initial results of the hydrologic investigation showed that, because of the unique hydrogeologic setting of the proposed mine, perimeter dewatering would be expensive through the life of the mine, technically difficult, and would have a measurable impact on the surface- and ground-water resources in the area. Subsequently, the use of various types of cutoff walls was evaluated as a means to reduce the amount of water to be pumped by eliminating ground-water flow into the pit. Numerical simulations indicated that use of a cutoff wall would significantly reduce costs, and would result in minimal impacts to the water resources and fish habitats. A frozen-earth wall was selected as the most cost-effective means of creating a cutoff wall.

Hydrogeologic Setting

Surficial sediments in the hydrologic study area (HSA) are the product of Wisconsinian glaciation, deposited until about 8,200 years ago.[1] Esker deposits left by retreating continental glaciers interfinger with and are overlapped by fine-grained pro-glacial lake sediments. Esker crests rise 5 to 20 m above the surrounding Abitibi clay plains, giving the region a slight relief. One such esker, the Kettle Lakes Esker, traverses the HSA from north to south, with a width of 500 to 1,500 m (Figure 1). Near the proposed Aquarius pit, the thickness of the esker deposits from the bedrock contact to the water table ranges from approximately 125 m along the eastern edge of the proposed pit to 20 m above isolated bedrock highs.

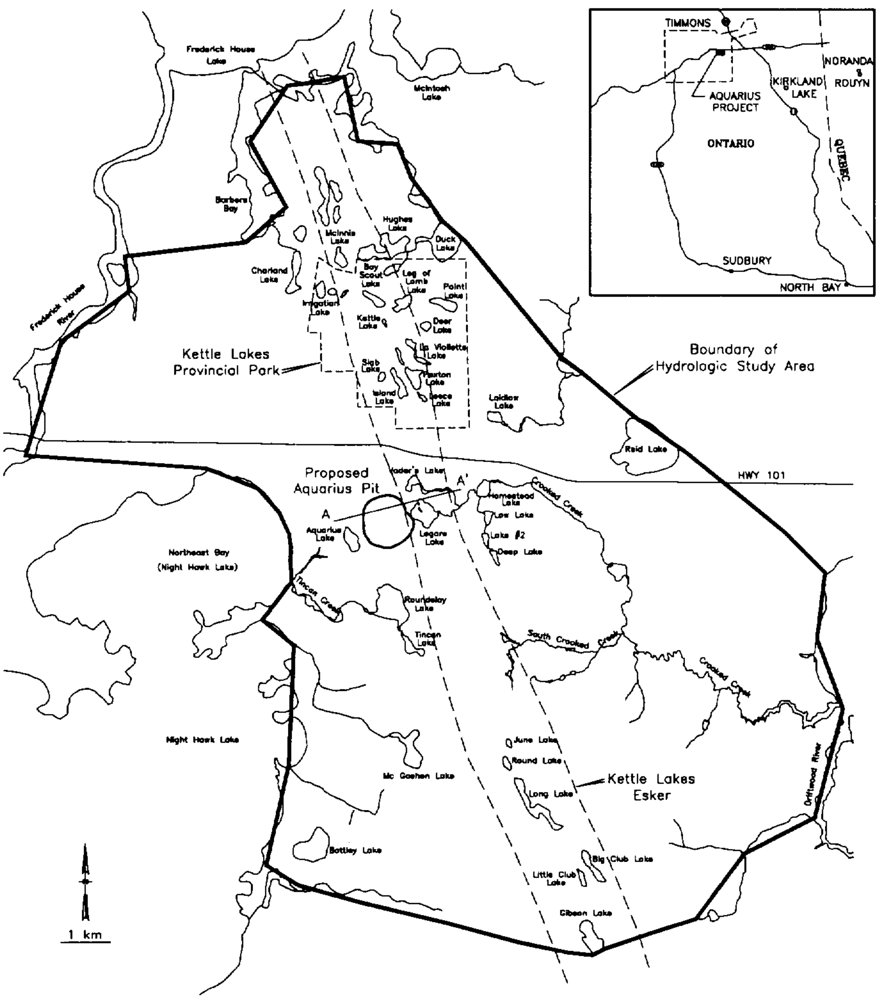

Fig. 1. Hydrologic Study Area

Ice-contact stratified drift comprises the core of the Kettle Lakes Esker, and consists of interbedded, sandy-pebble to cobble-gravel units that were deposited as traction bedload in confined meltwater flow.[1] Aquifer test data indicate a hydraulic conductivity of approximately 120 to 250 m/day in the esker core. Glaciofluvial sediments flank the core of the Kettle Lakes Esker, and consist of silty sands, fine-grained sands, and medium- to coarse-grained sands (Figure 2). The sands were deposited in a series of coalescing, alluvial-subaqueous fans projected into the proglacial lake as the glacier retreated. The hydraulic conductivity of the sands as determined from pumping tests is in the range of 2 to 22 m/day. Lake sediments consists of as much as 35 m of laminated to varved silts and clays that form the most extensive surficial deposits in the HSA. The silts and clays have hydraulic conductivities in the range of 0.001 to 0.5 m/day. Glacial till occurs locally in relatively small deposits on top of the bedrock and varies in thickness from 0 to 40 m. The till appears to be typical of compacted diamictons; and is assumed to have a hydraulic conductivity of approximately 10^{-3} to 10^{-5} m/day[2].

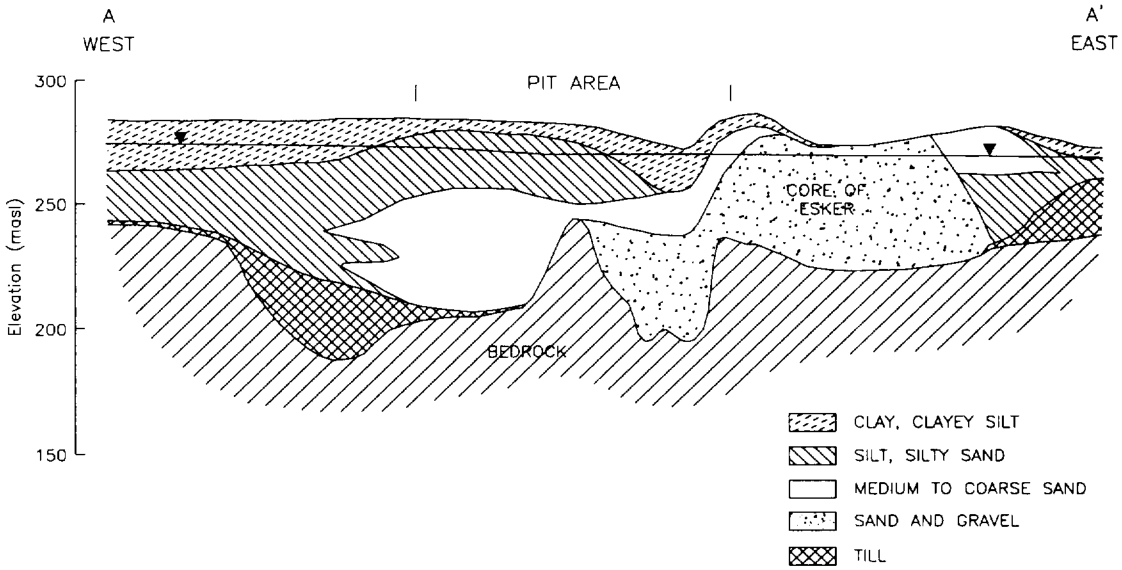

Fig. 2. Hydrogeologic Cross Section through the Proposed Pit

Bedrock beneath the HSA consists of Archean rocks, including mafic to ultra-mafic volcanics of the Tisdale Group, felsic volcanics of the Deloro Group, and metasedimentary units of the Timiskaming Series. The bedrock in the pit area consists of dark green chlorite-talc-carbonate altered rock that is variably and heterogeneously foliated to phyllite and schist. The Aquarius mineral deposit is located on a splay of the Destor-Porcupine Fault, which trends east-northeast. Ground-water inflows encountered during underground mining show the bedrock to be relatively impermeable. Consequently, the top of the bedrock is considered to be the effective base of the ground-water flow system. The topography of the bedrock surface is quite variable in the area of the proposed pit. Local depressions or troughs in the surface would contribute significantly to ground-water flow to the proposed pit.

The proposed pit straddles the contact between the esker deposits and overlapping silts and clays (Figure 2), so that saturated overburden above the west portion of the proposed pit is very tight, and above the east portion of the pit is highly conductive. The proposed pit intersects the edge of the Kettle Lakes Esker complex, which extends north into the Kettle Lakes Provincial Park, creating good hydrologic connection between the proposed mine dewatering and the lakes of the Provincial Park.

Numerous other lakes and small creeks are located throughout the HSA. Relatively shallow lakes that are located above surficial deposits of clays and silts generally drain to creeks and into the regional drainage system. Kettle lakes located along the esker are relatively deep and are usually centers of internal drainage. The area of the Kettle Lakes Provincial Park is a recharge area for the ground water that flows through the esker complex. Ground water discharges from the esker into Vader's, Homestead, and Legare Lakes, and into South Crooked Creek (Figure 1).

Annual precipitation in the Timmins area is approximately 800 to 850 mm per year and net evapotranspiration is approximately 380 to 450 mm per year.[3] Surface geology determines whether the net precipitation infiltrates to recharge the ground-water system, or becomes surface runoff. Depth to water averages 15 m throughout the HSA.

Evaluation of Dewatering Alternatives

The unique hydrogeologic setting of the Aquarius deposit required different dewatering options to be considered. Factors considered in evaluating different dewatering alternatives included dewatering costs, effects of dewatering on adjacent water resources, and operational considerations. The primary tool used in the evaluation was a numerical ground-water flow model.

The two primary methods of dewatering that were evaluated included conventional perimeter dewatering, and dewatering using a cutoff wall. A frozen-earth wall was selected as the method of cutoff wall construction because of its relatively low cost and the integrity of the seal it would provide. Conventional dewatering required incorporation of recharge basins and a complicated network of direct recharge to surface water bodies in order to mitigate impacts to the water resources. Use of a frozen-earth wall would eliminate most mitigation requirements. Both dewatering plans included pumping water into the pit after mining in order to accelerate pit infilling.

A three-dimensional, finite-element ground-water flow model was constructed to mathematically describe the hydrologic system in the HSA. The numerical model was used to evaluate various dewatering alternatives. By incorporating representations of the major hydrogeologic features of the ground- and surface-water system, the model is able to reasonably predict the response of the system to hydraulic stresses that would be imposed by proposed mine dewatering and pit infilling. The numerical model uses the flow code *FEMFLOW3D*.[4]

The model includes a finite-element grid containing 4,683 nodes and 7,746 elements. The grid in the pit area was finely discretized in order to provide better solutions for heads and fluxes near the area of flow convergence, and to reasonably represent the geometry of the proposed pit during mining simulations. Regionally, five layers were incorporated into the grid to simulate layering of the aquifer system. The total area of the model is about 120 km^2.

Predicted Effects of Conventional Mine Dewatering

A dewatering plan was developed based upon the results of model simulations. The plan included wells at the edges of each pit phase, the number of wells varying over time. The total number of wells needed to dewater the pit was estimated to be 295, pumping at rates of 1.5 to 115 L/s (Figure 3). Dewatering was simulated in three stages: pre-mining dewatering prior to initial stripping; mining; and, post-mining pit infilling. Mitigation of dewatering effects was accomplished in the simulations by routing water from the pit to infiltration ponds south of the Kettle Lakes Provincial Park, and to Roundelay, Homestead, and Tincan Lakes, and Crooked and Tincan Creeks. As a part of the conventional dewatering operations, it was determined that Legare, Vader's, and Aquarius Lakes would have to be drained for both dewatering and pit-slope stability purposes.

Dewatering was simulated for a period of 8.5 years, and pit lake infilling for an additional 3 years after mining and dewatering ceased. The simulations predicted that the amount of water to be managed through dewatering wells and sumps in the pit would range from about 4,300 L/s during the first 18 months of conventional dewatering to approximately 3,000 L/s during the last seven years of dewatering (Figure 4).

Predicted drawdowns in the water table due to dewatering of the Aquarius pit at the end of dewatering, for conventional dewatering, are shown in Figure 5. The maximum predicted drawdown was in the range of 100 to 110 m immediately adjacent to the edge of the pit. In general, the extent of drawdown -- defined by the extent of the 1-m drawdown isopleth -- would elongate along the trend of the esker system to June Lake in the south, to Roundelay Lake on the southwest, to Crooked Creek in the east, and to the infiltration ponds on the south side of Kettle Lakes Provincial Park to the north of the proposed pit. Changes in lake levels due to dewatering would be a function of the recharge and the nature of the materials on the bottom and sides of each lake.

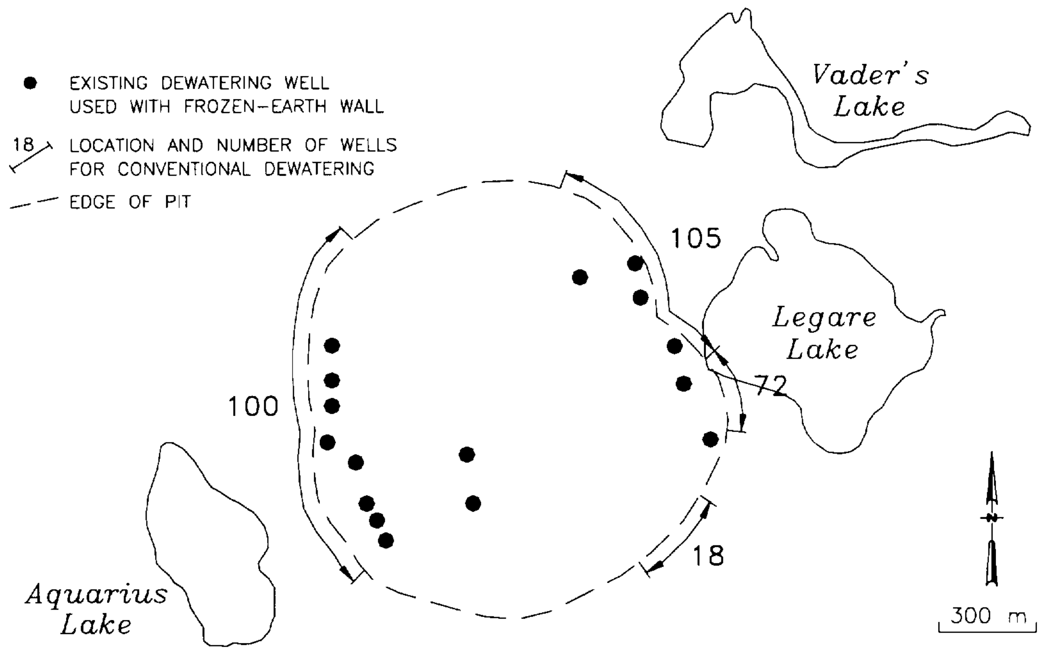

Fig. 3. Location of Simulated Dewatering Wells

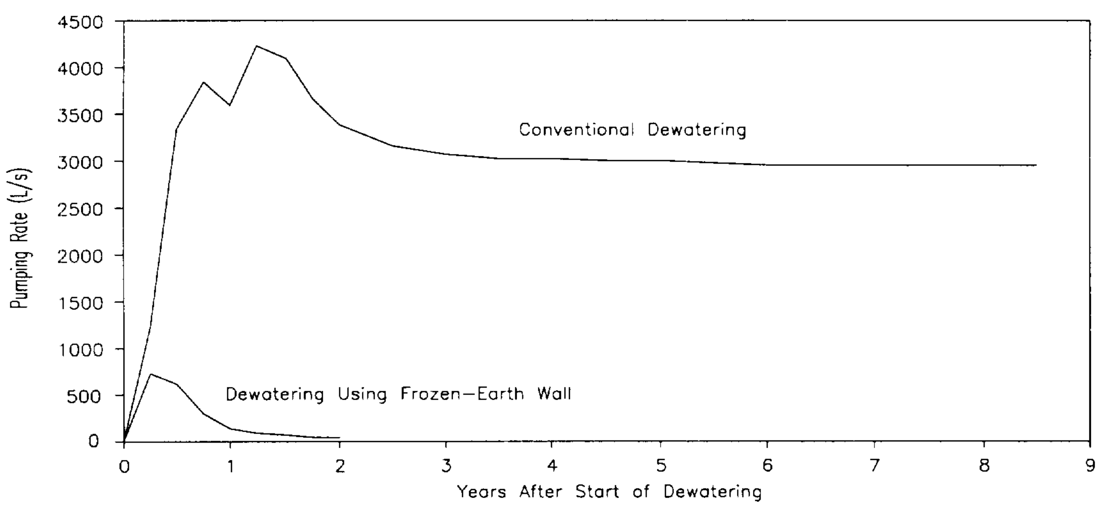

Fig. 4. Estimated Dewatering Rates

After 8.5 years of dewatering, all dewatering wells and sump pumps would be turned off, and the Aquarius Pit would begin to fill with ground water to form a "pit lake." Pit infilling simulations assumed that water would be pumped from Night Hawk Lake to the northern infiltration ponds and to Roundelay and Homestead Lakes, in order to continue maintaining water levels in those areas, as well as directly back into the pit (Figure 6). The simulations assumed that water would be pumped from Night Hawk Lake at a rate of 2,900 L/s. Initially, 600 L/s would be routed to the pit and 2,300 L/s to the infiltration ponds and lakes.

Simulations showed that conventional dewatering, with mitigation measures, would not have a significant effect on most of the surface-water bodies. The largest effect would be to Low, #2, and Deep Lakes where drawdowns were estimated to be greater than the maximum depth of the lakes (approximately 10 to 20 m). The predicted decline of ground-water extends to June to the south; Night Hawk Lake would not be impacted from mine dewatering or pit lake infilling. In general, the impacts to the streams would be minimal. The main stem of Crooked Creek and Tincan Creek would be mitigated by pumping mine water to the streams.

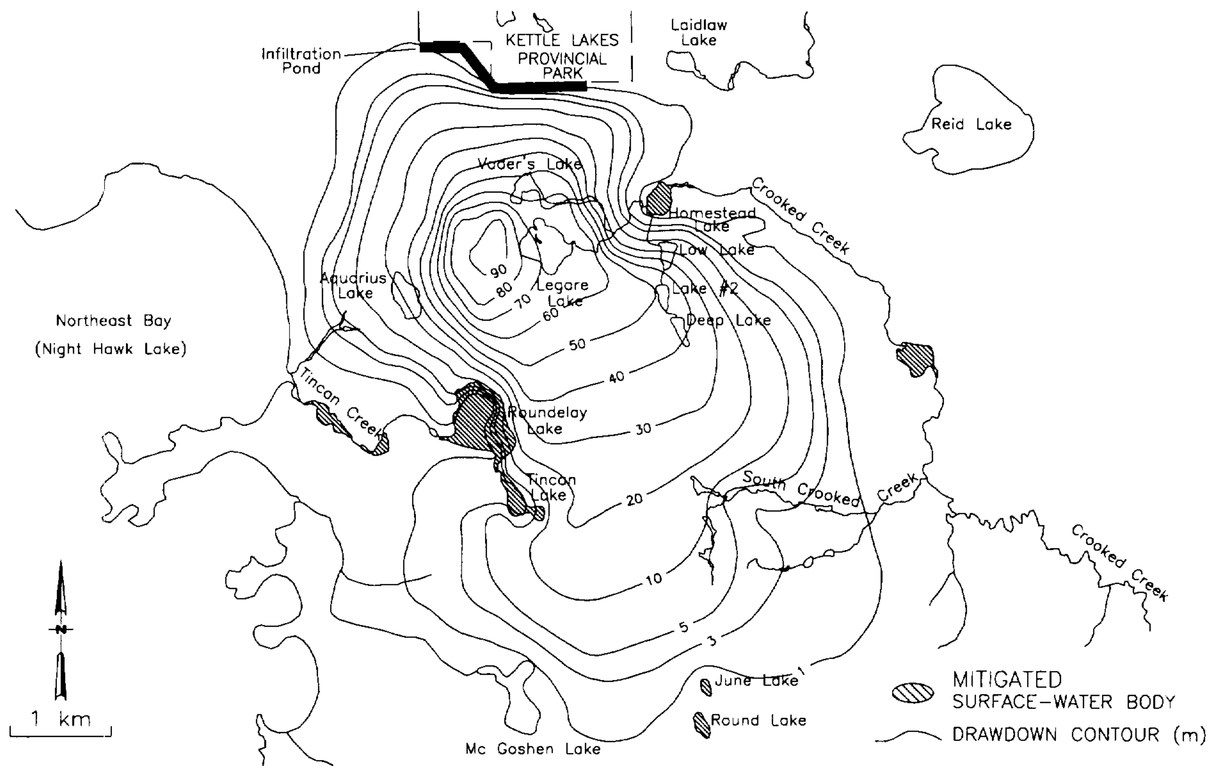

Fig. 5. Estimated Drawdown at the End of Mining Due to Conventional Dewatering

Predicted Effects of Dewatering Using Frozen-Earth Wall

The numerical model was used to evaluate the use of a frozen-earth wall. The advantage of using a frozen-earth wall is that only water in storage inside the wall needs to be removed, and the hydrologic effects of dewatering are minimal, outside of the wall. The frozen-earth wall was simulated using a finely-discretized ring of elements around the perimeter of the pit extending from the top of bedrock to the top of the model. Elements used to simulate the frozen-earth wall were assigned a hydraulic conductivity of 0.001 m/day.

Dewatering was simulated for a period of 3.5 years, and mining was assumed to be completed 10 years after the frozen-earth wall was constructed. Wells were simulated within the pit, the number of wells varying as the shallower portions of the alluvium are dewatered first. The total number of wells needed to dewater the pit, in conjunction with the frozen-earth wall, was estimated to be 15, pumping at rates of 1.5 to 115 L/s. The water would be managed through a combination of pumping from dewatering wells and from in-pit sumps, which would collect any residual passive inflow or water from horizontal drainholes inside the frozen-earth wall. Water pumped from within the frozen-earth wall would be discharged primarily Roundelay Lake with some discharge to Crooked Creek. The estimated amount of water that would have to be managed varied from about 40 to 700 L/s during the first 2 years of mining (Figure 4).

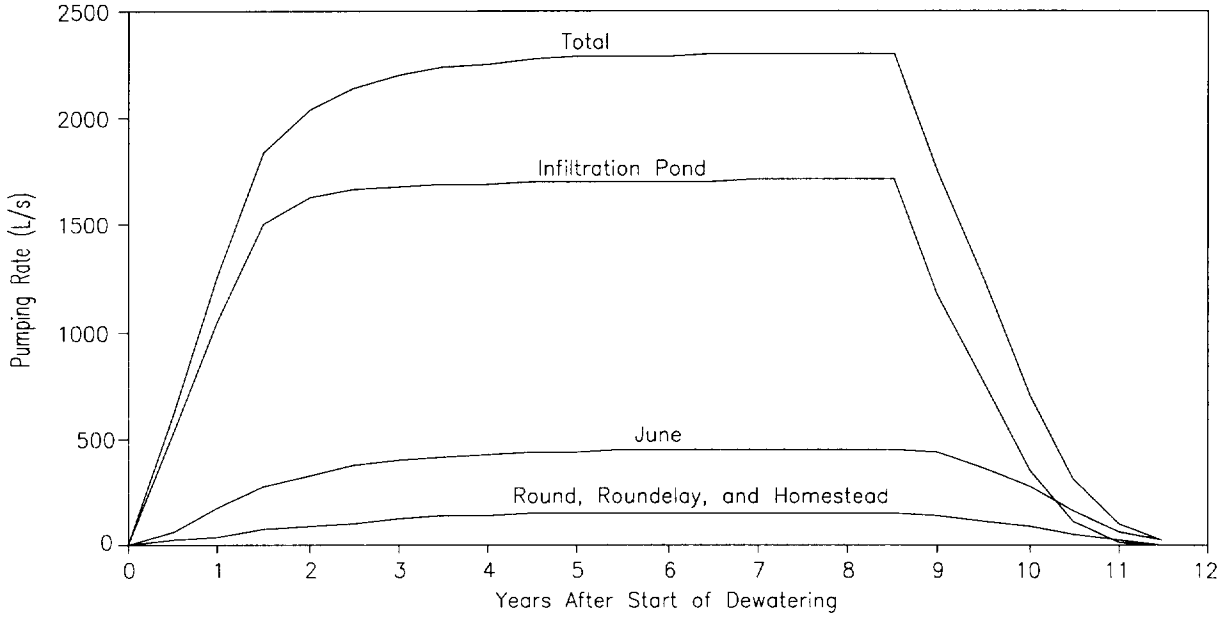

Fig. 6. Estimated Recharge Needed to Maintain Water Levels in Adjacent Lakes Due to Conventional Dewatering

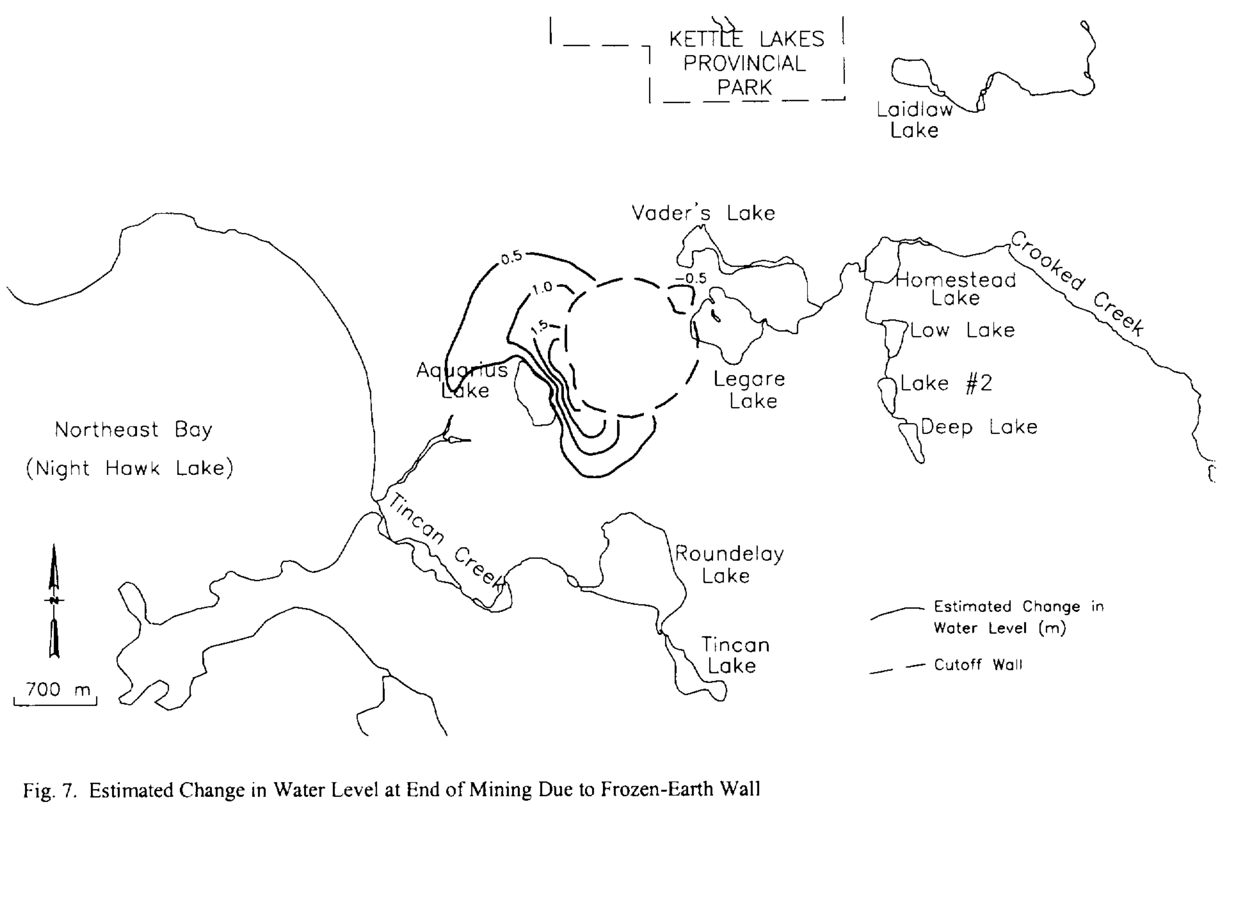

Fig. 7. Estimated Change in Water Level at End of Mining Due to Frozen-Earth Wall

The predicted changes to the ground-water flow system as a result of constructing the frozen-earth wall are relatively minor. In general, there was a slight increase in water levels on the west side of the pit due to damming of ground water flowing toward Legare Lake and Crooked Creek (Figure 7). A small ground-water depression of approximately 0.5 m was predicted to occur on the eastern side of the pit. This depression is the result of reduced flow from the west as a result of the frozen-earth wall.

The model predicts that the proposed mining operation using a ground-water cutoff wall will not have a significant effect on surface-water bodies. Ground-water flow to Legare Lake and Crooked Creek will be reduced by a maximum of 9 L/s.

It was assumed that the frozen-earth wall would remain intact after mining, long enough to fill the pit with water pumped from Night Hawk Lake. A simple stage/volume relationship was used to determine that approximately 20 months would be required to fill the pit lake at an average inflow rate of 1,500 L/s.

Predicted drawdown in the water table, 100 years after mining is shown in Figure 8. A new water table will be established after the pit lake forms. The depression of the water table is caused by water levels in the pit lake being slightly lower than the pre-mining water table in the aquifer on the western side of the proposed pit. The configuration of the post-mining water table will be similar for any pit lake that will be created, regardless of the method of dewatering.

Frozen-Earth Wall Construction and Monitoring

The frozen-earth wall consists of a fence of 2,243 vertical freeze pipes, installed along the 3,500-m perimeter of the planned pit. Boreholes are spaced on approximately 1.8 m centers, and were drilled through overburden (30.2 to 143.6 m, averaging 84.7 m thick) and completed 3 m into bedrock (Figure 9). Every 10th hole was drilled 6 m into bedrock for verification that bedrock was encountered. Core drilling, and down-hole geophysics were also used to distinguish bedrock contacts from large boulders.

Following the drilling and placement of freeze pipes, each pipe was surveyed to determine the bottom-hole spacing. Where distance between borings drifted more than design parameters, additional freeze-pipes were installed to reduce pipe spacing to within design tolerance. All freeze-pipes were pressure tested to ensure that no brine could escape into the environment.

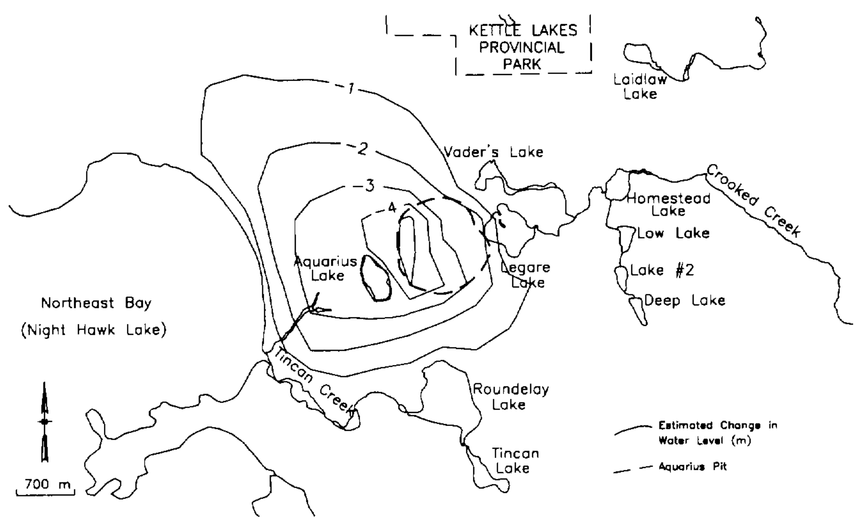

Fig. 8. Estimated Change in Water Level 100 years After Mining

The formation of the frozen barrier at any point along the pit perimeter is dependent upon the thermal conductivity of local soils, local ground-water velocities, initial ground-water temperatures, refrigeration loading, circulating brine temperature, and the spacing between the adjacent freeze pipes. It is anticipated that it will take approximately 20 to 25 weeks to form a continuous barrier.

The freeze pipes will be chilled by two identical ammonia refrigeration plants. Each plant contains five, 900 hp compressors, four evaporative condensers, four titanium heat exchangers, and four, brine-circulation pumps that have been designed to deliver 5,000 tons/hour of refrigeration at –20°C. The system will chill calcium chloride ($CaCl_2$) brine to –20°C, and distribute it through High Density Polyethylene (HDPE) manifolds to four quadrants of freeze-pipes around the pit. The brine will flow at 1 L/s from the manifolds to freeze-pipes, which are clustered with between two and eight individual freeze-pipes. The brine will flow from the manifold discharge line down the center of a 38 mm diameter HDPE pipe, which is located inside a 76-mm diameter, schedule 40 steel pipe. Flow back to the surface will be through the annulus of the steel pipe and sequentially to each freeze-pipe along the cluster. The brine will then be returned to the freeze plants through the return header to be chilled again to –20°C (Figures 9 and 10).

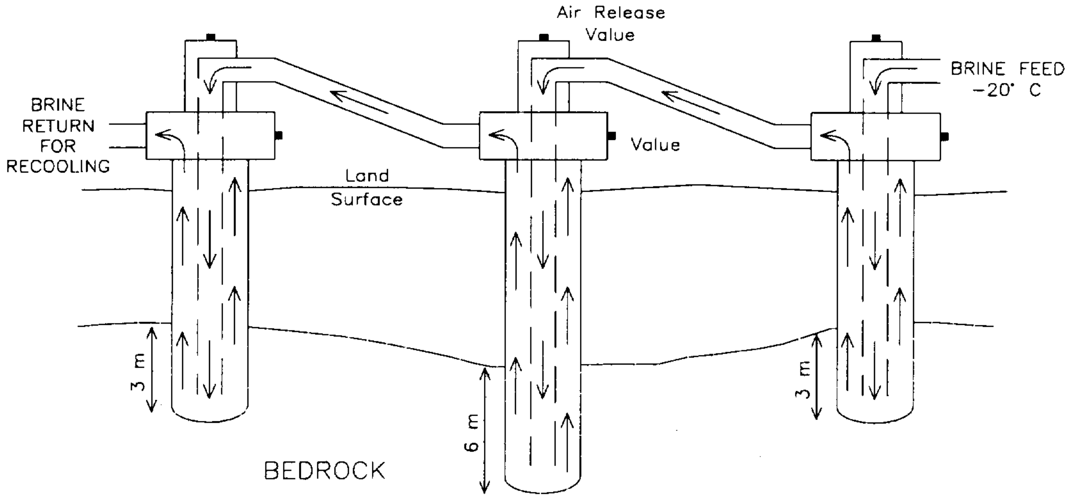

Fig. 9. Schematic Diagram of Freeze-Pipe Installation

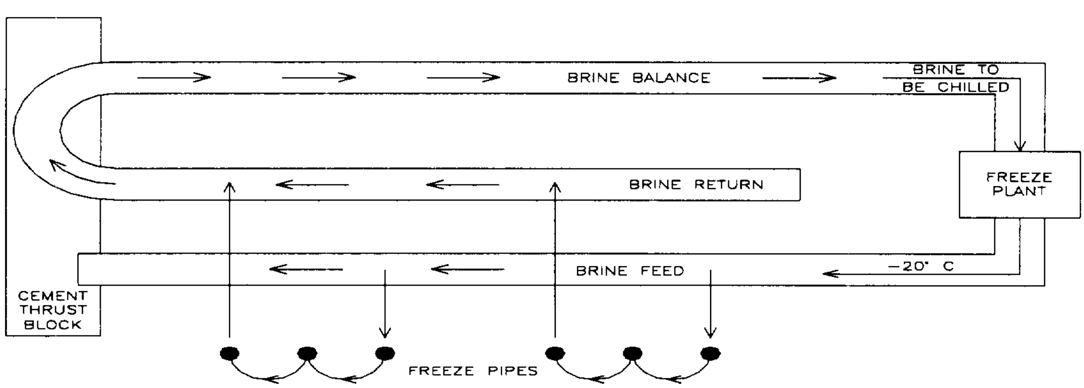

Fig 10. Schematic Diagram of Freeze System

The freeze wall will be carefully monitored through a comprehensive data collection system. Monitoring parameters will include temperature, brine-flow rates, brine pressure, and ground-water levels on either side of the freeze wall. The Aquarius freeze project has been designed so that the temperature sensors, pressure transducers, flow systems and freeze plants can be monitored and evaluated in real time. The data system can be monitored via a telephone line linked to a computer for data acquisition. Included in the fence of freeze-pipes are 91 temperature monitoring pipes, which are identical in construction to the freeze-pipes except that they are not connected to the brine manifolds. These temperature pipes are designed to measure the coolant temperature; a consistent brine temperature will be indicative of a completed frozen earth wall. A series of sensing devices inside the brine filled temperature pipes will measure the temperature of the frozen earth wall at various depths.

To verify that brine is being delivered uniformly at 1 L/s, the manifold system is equipped with eight flow sensors linked to magnetic flow-meter converters. There are also 25 pressure transducers, at selected intervals, around the piping to detect any pressure drops, which may result from a brine leak. The transducers are designed to measure pressure drops of 10 psi and trigger waning alarms. The design operating pressure for the system is 125 psi. A total of approximately 90 piezometers will be placed on either side of the freeze wall. The piezometers inside the freeze wall will monitor water-level changes during the dewatering of the pit. The exterior piezometers will be placed opposite the interior piezometers to evaluate ground-water flow conditions imposed by the frozen-earth wall.

Summary

The proposed Aquarius open-pit mine is overlain in part by esker sediments that would transmit prohibitive quantities of water to the mine during excavation. Studies indicate that a conventional dewatering system would be expensive, and have impacts to local surface-water bodies (including the Kettle Lakes Provincial Park). Numerical modeling simulations indicate that the use of a frozen-earth wall will minimize the effects of dewatering on the adjacent water resources by cutting off all alluvial flow into the pit. Operational expenses will be reduced because only water within the footprint of the frozen-earth wall will have to be pumped. Upon completion of mining, the pit lake will be connected to Legare Lake on the east side enhancing the existing fishery.

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