Design of Open Pit Dewatering System - Minago Project, Grand Rapids, Manitoba

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ABSTRACT
Victory Nickel is undertaking a Feasibility Study for a proposed open pit mine for a nickel deposit in central Manitoba, Canada. The geology consists of overburden, limestone, sandstone, and granite. As the limestone and sandstone form an extensive confined aquifer system, pit dewatering will be required in advance of mining. Piezometric response recorded during a four-well, long-duration pumping test program was used to develop a numerical hydrogeologic model which was then used to design a full-scale dewatering system. Approximately 12 dewatering wells completed along the crest of the ultimate pit and operating simultaneously at 40,000 m^3/day would be required.

RÉSUMÉ
Victory Nickel entreprend une étude de faisabilité d'un gisement de nickel au Manitoba central, Canada. La géologie est : mort-terrain, chaux, grès et granite. La chaux et le grès forment un système régional d'aquifères confinés, ainsi le dénoyage de la mine devra être fait. La réponse piézométrique enregistrée pendant un essai de pompage longue durée sur quatre puits a été employées pour développer un modèle hydrogéologique numérique utilisé pour la conception du système de dénoyage complet de la mine. Cette étude conclu qu'il faudra approximativement 12 puits d'assèchement longeant la crête de la mine et fonctionnant simultanément à 40 000 m^3/jour.

1 INTRODUCTION

The Minago Project is one of Canada's largest sulphide nickel deposits and is owned by Victory Nickel Inc. The Site is located in central Manitoba (Figure 1) in the Thompson Nickel Belt, about 100 kilometres north of Grand Rapids, and about 2 kilometres west of Provincial Trunk Highway #6. In addition to the metal deposit, the cap rock includes a basal sandstone unit that contains hydraulic or fracturing (frac) sand, a material used to enhance recoveries in the oil and gas industry. An open pit mine has been proposed to extract the nickel deposit and the frac sand as a byproduct.

The site lies within the Manitoba Lowland, which comprises much of the southern and central portion of the province, and is situated at the boundary between the Nelson River Watershed and the Lake Winnipeg Basin (Betcher, et al., 1995). Peat bog and boreal forest vegetation exists across the Site and conditions at the surface remain frozen for approximately six months of the year. Bedrock is covered over much of the Site by Quaternary overburden (approximately 1 m of peat moss overlying 5 m of clay) of glacial or lacustrine origin. Bedrock geology at the Site consists of Ordovician dolomitic limestone of the Red River formation (approximately 55 m thick) and quartzose sandstone of the Winnipeg formation (approximately 10 m thick) overlying Precambrian igneous and metamorphic rocks of the Canadian Shield (Betcher, et al., 1995), which include mineralized zones of the Thompson Nickel Belt. The upper 30 m of the limestone unit appeared to contain a higher proportion of water-bearing features relative to the lower portions of the limestone. The general stratigraphic sequence is presented in Figure 2.

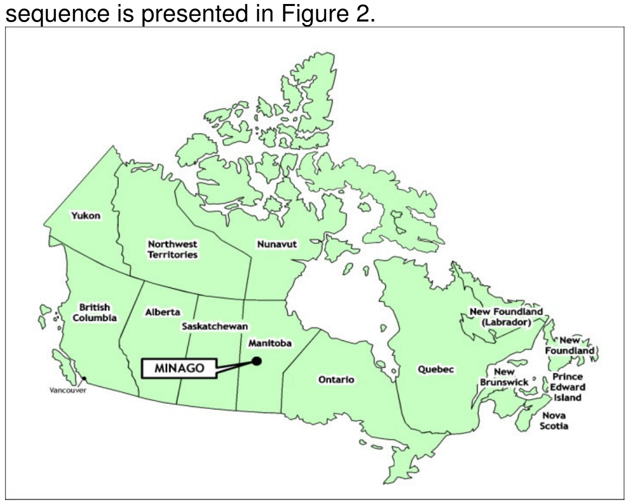


Figure 1. Location Plan

Hydrogeologic investigations were undertaken at this Site to estimate the dewatering requirements for the proposed open-pit mine, in support of Victory's mine feasibility study and permitting. This included a multi-well, long duration, pumping test program, the development of a conceptual hydrogeological model of the Site, and the subsequent construction and calibration of a groundwater flow model of the proposed open pit area. The numerical model was then used to estimate the dewatering requirements for the proposed open pit.

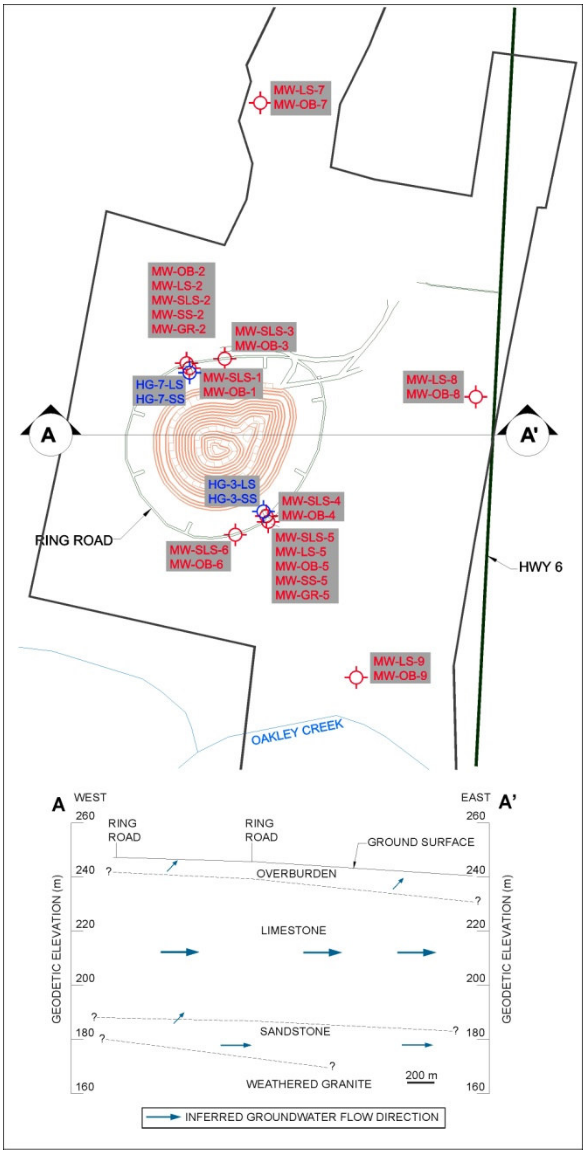


Figure 2. Map Showing the Proposed Open Pit and Wells used during Pumping Test, and Section with Hydrostratigraphy

2 PUMPING TEST PROGRAM

The pumping test program involved the pumping of four bedrock dewatering wells located along the perimeter of the proposed open pit mine, and monitoring the hydraulic response in these pumping wells and in twenty-four observation wells (Figure 2). The objective of this test program was to obtain site-specific hydrogeologic information to provide data for the development of a numerical model to be used in support of the dewatering system design. The dewatering wells were installed at two locations (HG-7 and HG-3) along Ring Road which encircles the proposed pit area. At each location two wells were completed: one that penetrated the full thickness of the limestone unit (LS) and one that penetrated the full thickness of the sandstone unit (SS). Observation wells were installed at a total of nine locations, at distances of approximately 40 m, 80 m, 300 m, and 2,000 m from each dewatering well. The shallow limestone (SLS) observation wells monitored the upper three meters of the unit while the limestone (LS) observation wells monitored the remaining thickness of the unit (generally about 50 m thick). The placement of the observation wells at various distances from the pumping wells and at various elevations (i.e. within the four primary hydrostratigraphic units that will be exposed by the proposed pit) resulted in an instrumentation array that allowed the monitoring of the three-dimensional drawdown response resulting from pumping. The instrumentation array was comprised of pressure transducers equipped with data loggers. Well installation and equipment setup prior to testing took considerable time due to poor access and difficult ground conditions (Figure 3).

The pumping test program included four six-hour step-drawdown tests to determine the optimum pumping rate for each dewatering well for the multi-well pumping test, a seven-day multi-well pumping test to estimate the hydraulic properties of the high permeability limestone and sandstone units, followed by eight single-well response tests to estimate the hydraulic properties of the low permeability overburden and granite units.

The pumping test consisted of five days of pumping and two days of recovery (Figure 4). Pumping in the dewatering wells was initiated sequentially, on separate days, such that pumping at HG-7 LS began at the start of Day 1, at HG-3 LS at the start of Day 2, at HG-7 SS on Day 3, and at HG-3 SS on Day 4. On Days 4 and 5, all the wells were pumped simultaneously, at a combined rate of approximately 8,300 m^3/day. At the start of Day-6, all the pumps were turned off and well recovery monitoring occurred over Days 6 and 7.

Pre-pumping hydraulic heads in the limestone unit were above those in the overburden unit at all the well locations except those in the vicinity of HG-7 (including MW-1, MW-2, and MW-3), where hydraulic heads in the limestone were only slightly below those in the overburden. During the pumping test, the hydraulic head in the limestone was lowered below the top of the limestone in the region within 75 m to 300 m of HG-7 and the region within 40 m of HG-3. However, the ground surface remained saturated, and the maximum drawdown in the overburden did not exceed 0.06 m.

The results of the pumping test were analyzed using two methods. First, an analysis was performed using conventional straight-line and curve-fitting techniques for pumping test analyses that are based on analytical models of well hydraulics. The second method consisted of using a local-scale numerical hydrogeologic model, based on concepts presented by Walton (2008).

2.1 Conventional Straight-line and Curve-Fitting Analyses

The pumping test analysis progressed from the least complex solution (Cooper and Jacob 1946 distance-drawdown method) to more complex analytical models that considered leakage, heterogeneous conditions, and boundary conditions (Butler’s 1988 solution for a heterogeneous confined aquifer, and Moench and Prickett

1972 solution for homogeneous confined aquifer undergoing conversion to unconfined conditions).

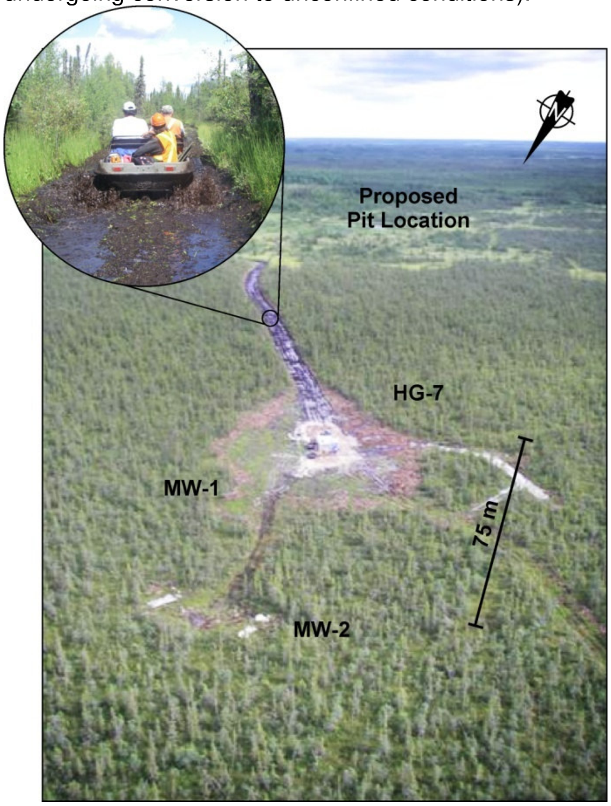
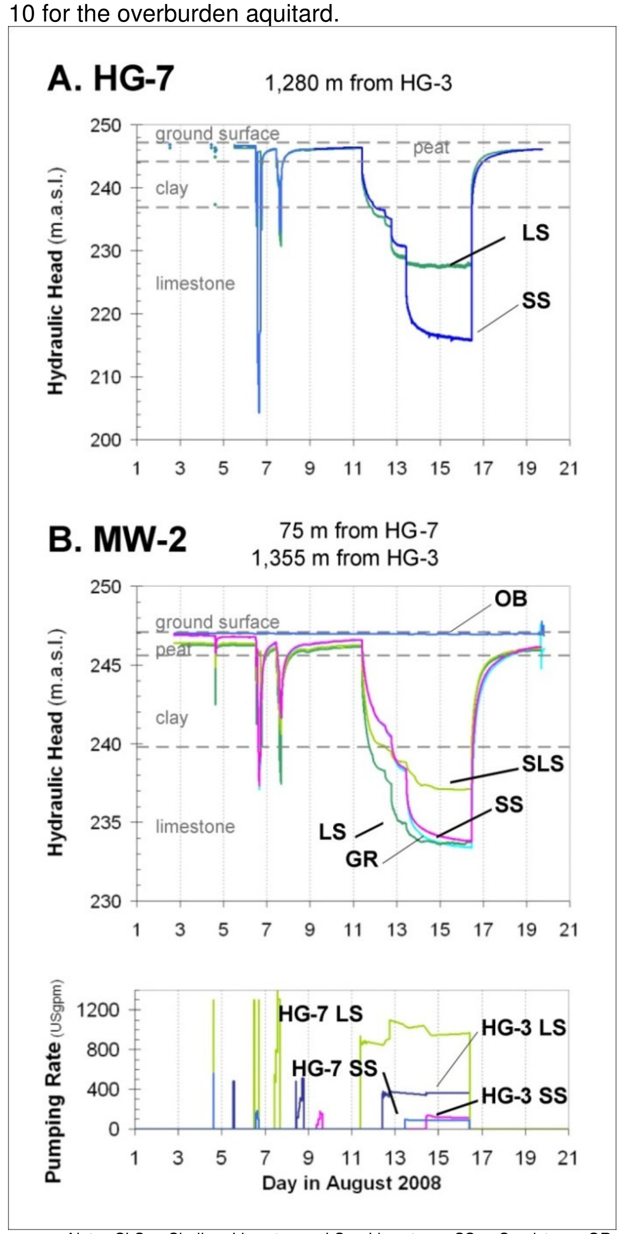


Figure 3. View of Pumping Well Location HG-7

An example plot showing the distance versus drawdown observed at a time of 4.6 days during the pumping test (approximately at the end of pumping) in the limestone (LS) observation wells nearest to pumping well HG-7, and the best-fit straight-lines is presented on Figure 5. The limestone observation wells were chosen as they exhibited the greatest drawdown compared to the shallow limestone observation wells and the sandstone observation wells, indicating a higher permeability. The drawdown observed at this time was considered representative of "late-time" data that is generally applicable to distance-drawdown analysis.

The results of the straight-line and curve-fitting analyses indicated that the limestone aquifer was laterally heterogeneous. The transmissivity of the limestone aquifer was three times greater in the vicinity of HG-7 (north area of the pit) relative to all the other areas of the pit, including the area of HG-3 to the south.

To assess the vertical hydraulic conductivity of the overburden clay aquitard, the Hantush-Jacob (1955) steady state solution for leaky aquifers was employed. In this method, the leakage and vertical hydraulic conductivity of this unit was estimated from i) the measured late-time hydraulic head data, ii) the calculated transmissivity of the underlying limestone and iii) the pumping rate in the nearest pumping well. The vertical hydraulic conductivity estimates from the more distant overburden observation wells were considered most representative because leakage generated by the aquitard became a larger portion of the well discharge with greater distance from the pumping wells. Based on the results from the overburden wells situated at least two kilometers from the pumping wells, the vertical hydraulic conductivity (K_V) of the overburden was estimated to be an order of magnitude less than its horizontal hydraulic conductivity (K_H), as determined from slug test analyses. This indicates an anisotropy ratio (K_H/K_V) of approximately 10 for the overburden aquitard.



Note: SLS – Shallow Limestone; LS – Limestone; SS – Sandstone; GR – Weathered Granite.

Figure 4: Hydraulic Head in HG-7 and MW-2 and Pumping Rates during the Pumping Test Program

2.2 Analysis Based on a Local-Scale Numerical Model

Although the analytical models used in the above analyses incorporate the general features of the flow system near the dewatering wells, they include several simplifying assumptions that may affect the accuracy of the estimates of hydrogeologic parameters. For example, the analytical models cannot account for simultaneous pumping in both the limestone and sandstone aquifers. To address this and other limitations in these methods, additional analysis of the pumping test was undertaken using a local-scale numerical hydrogeologic model. This approach was suggested by Walton (2008) for hydrogeological settings of hydrogeologic complexity, such as the ones at the Minago Project. This model was developed using FEFLOW (Diersch, 2008), a finite element modelling code capable of simulating transient groundwater flow and transport in three-dimensions under a variety of boundary conditions. Of particular relevance to this analysis was FEFLOW's ability to represent transient changes from confined to unconfined conditions in a heterogeneous aquifer.

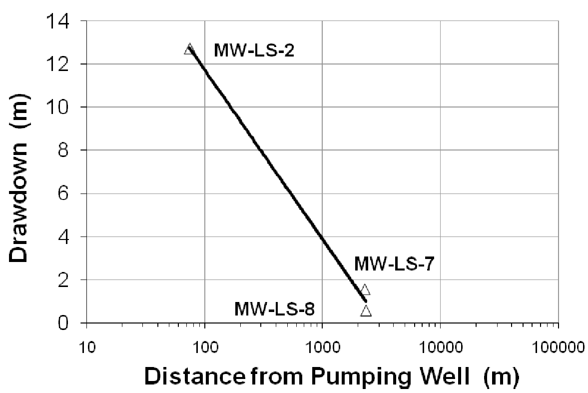


Figure 5. Distance-Drawdown Measured in Limestone nearest to Pumping Well HG-7.

The local scale model was centered on the proposed open pit and extended approximately 5 km from this center based on the observed maximum extent of the drawdown cone during the pumping test (approximately 3 km). Vertically, the model was divided into eight layers: layers one and two represented the overburden, layers three and four represented the limestone unit, layer five represented the sandstone unit, and the bottom three layers represented the granite. The horizontal mesh spacing graded from approximately 1.5 m near pumping wells HG-3 and HG-7 to 100 m away from these wells. Based on the principle of superposition, only the drawdown response was simulated with this model and the regional groundwater flow was not represented.

The pumping test was simulated by assigning specified flux boundaries at the locations of wells HG-3 and HG-7. These boundaries were assigned in the limestone and sandstone units, and the flux values were based on the pumping rates measured during the 5-day test. The hydrogeologic parameters determined from the analytical methods were assigned to the finite element mesh. The model was run for a period of seven days (five days of pumping and two days of recovery). Initially, several manual calibration runs were conducted, where individual model parameters were incrementally adjusted to improve the match between simulated and measured drawdown at the observation wells. The calibration was then refined using an automated procedure that utilized the parameter estimation code PEST (Doherty, 1999).

Figure 6 presents the drawdown cone predicted by the calibrated model for the limestone unit at the end of the 5-day pumping period. The predicted spatial extent and magnitude of the drawdown cone in limestone is in good agreement with field observations. The model was also capable of accurately predicting the drawdown response over time in the overburden, sandstone, and granite.

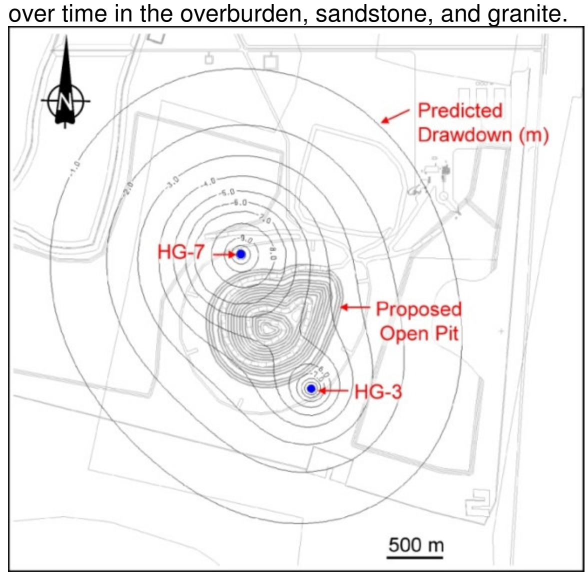


Figure 6. Drawdown Predicted by the Calibrated Local-Scale Model

The following Table 1 summarizes the hydrogeologic parameters determined through calibration of the local-scale model.

Table 1. Summary of Hydrogeologic Parameters from Numerical Analysis of Pumping Test Data

Unit	OB	LS	LS (HG-7 Area)	SS	GR
K (m/s)	1.0×10^{-8}	3.5×10^{-5}	1.3×10^{-4}	1.0×10^{-6}	1.0×10^{-8}
S_s (m^{-1})	1.0×10^{-4}	2.0×10^{-6}			
S_y (-)	n/a	2.5×10^{-2}			

Note:
OB – Overburden
LS – Limestone
SS – Sandstone
GR – Weathered Granite

3 DEWATERING SYSTEM DESIGN

The results of the pumping test program were used to update the conceptual understanding of groundwater conditions at the Site. This understanding was then incorporated into an expanded hydrogeologic model that was then used to design of the full scale dewatering system.

3.1 Conceptual Hydrogeologic Model

A hydrogeological conceptual model is a pictorial and descriptive representation of the groundwater regime that organizes and simplifies the hydrogeology. It must retain enough complexity so that the numerical model developed from it adequately reproduces or simulates the real groundwater flow behaviour. Based on the results of the pumping test program, the regional hydrogeological setting and borehole log descriptions, the following describes the conceptual model for the upper 75 m of the subsurface at the Site.

The limestone aquifer forms the main aquifer at the Site. The limestone aquifer is confined by the overburden clay deposit: a 5 m-thick aquitard. The ambient groundwater flow direction in the limestone is from west to east. During pumping, the water level in the limestone was lowered below the top of the limestone (i.e., below the bottom of the overburden unit) within about 100 m of the dewatering wells, under the pumping rates of the pumping test. In these regions, the limestone aquifer becomes unconfined and groundwater is released through aquifer drainage. Some amount of leakage from the overburden aquitard into the limestone aquifer occurs, providing some additional flow to the dewatering wells. The sandstone aquifer is affected by pumping in the limestone and has a comparatively lower permeability. The weathered granite that is in direct contact with the sandstone aquifer is likely more permeable than the underlying non-weathered granite. The non-weathered granite likely acts as a lower confining unit, or an aquitard, that provides minimal leakage to the sandstone unit, possibly through vertical fractures.

3.2 Expanded Numerical Model

The design, location and spacing of the dewatering wells for the full scale dewatering system were evaluated using a numerical hydrogeologic model for the entire Site. Figure 7 presents the extent of the model domain and the details of the finite element mesh. Horizontally, the model extends approximately 50 km in both the east-west and north-south directions, and was centered on the proposed open pit. Horizontal mesh spacing varied from approximately 30 m in the area of the proposed pit to about 500 m elsewhere in the model, which allowed for steep hydraulic gradients that are expected to develop near the pit in response to pumping. Overall, the model encompassed an area of approximately 2,470 km^2.

Vertically, the model was divided into the same eight layers utilized by the local-scale numerical model described above. The elevation of the top of the model was set to the ground surface. Where overburden was not present at limestone outcrops the upper most layers were assigned limestone properties. At greater distances from the proposed open pit the overburden, the limestone and sandstone units were assumed to have similar thicknesses as observed near the proposed pit and the limestone unit was assumed to dip gently towards the northeast in agreement with regional data presented in Betcher et al. (1995). The base of the model was set at 100 m beneath the sandstone/granite contact.

Three types of boundary conditions were used in the model: specified head, specified flux, and no-flow (zero flux). Specified head boundaries were used to simulate all lakes, rivers, and creeks, including William Lake to the southwest of the site, Winnipeg Lake to the southeast, Kiskit Lake to the northeast, Minago River to the north, and Oakley Creek to the south. It was assumed that all the lakes and the Minago River are in direct hydraulic connection with the limestone unit. All other streams were assumed to be underlain by overburden. In addition, a specified head boundary was assigned along the portion of the west model edge to represent regional flow of groundwater from limestone outcrops located west of the model domain. Finally, specified head boundaries, constrained to allow outflow of groundwater only, and set to ground elevation, were applied along the top of the model. These boundaries represented seepage faces and water-logged areas in portions of the model where artesian conditions in the limestone unit are expected.

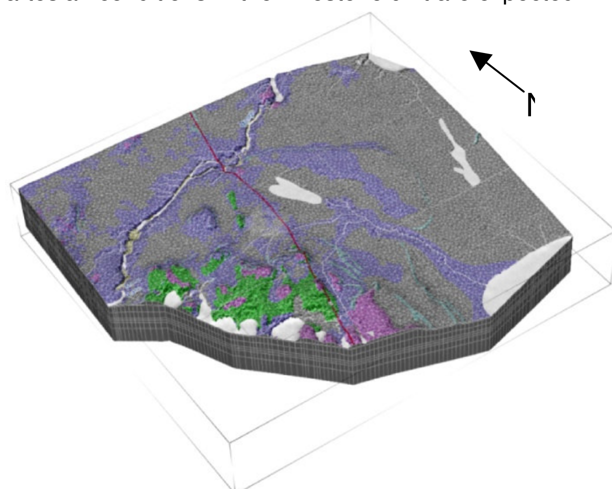


Figure 7. Model Domain and Finite Element Mesh

Specified flux boundaries were used to represent groundwater recharge from precipitation. These boundaries were assigned everywhere in the top layer of the model, and it was assumed that recharge values would be higher in the areas of limestone outcrops southwest and west of the site, and lower in the areas underlain by the overburden. Recharge values were adjusted during model calibration. A specified flux boundary was also assigned along the bottom of the model to simulate the observed upward hydraulic gradient between the granite and limestone units. This flux value was also adjusted during model calibration.

No-flow boundaries (zero flux) were applied along an inferred flowline north and south of the Site. A no-flow boundary was also assigned to an area east of the Site, between Kiskit Lake and Winnipeg Lake, in the direction where regional data suggest that the limestone unit may be pinching out. Because the locations of these no-flow boundaries were somewhat arbitrary, preliminary model simulations were completed to establish that these boundaries would not be intersected by the drawdown cone created during mine dewatering.

The hydrogeologic parameters estimated for the area near the pumping wells resulting from the calibration of the local-scale model were transferred to the expanded model for subsequent calibration to static hydraulic heads and baseflow measurements in the Minago River and

Oakley Creek. During model calibration, adjustments were made to the hydraulic conductivity of the limestone aquifer at distances greater than approximately 3 km from the pumping wells, and to the flux values representing recharge to groundwater flow from precipitation and upward groundwater flow from the granite unit. Hydrogeologic parameters representing other hydrostratigraphic units and the limestone aquifer in the vicinity of the 5-day pumping test were not changed from the ones arrived at during calibration to the pumping test.

Figure 8 presents the groundwater flow pattern in the limestone unit predicted by the calibrated model for pre-pumping conditions. In agreement with the Site conceptual model, the predicted groundwater flow direction near the proposed open pit was towards the east under a relatively moderate horizontal hydraulic gradient. This flow was predicted to occur in response to groundwater recharge at the limestone outcrops located southwest and west of the site, and to a lesser degree, recharge to the overburden. Groundwater flowing through the area of the proposed pit was predicted to discharge to Oakley Creek east of the site and to Lake Winnipeg to the southeast. As presented on the cross-section in Figure 8, the calibrated model correctly reproduced upward groundwater flow through the overburden; artesian conditions in the limestone unit near the proposed pit; and the upward hydraulic gradient between granite and limestone.

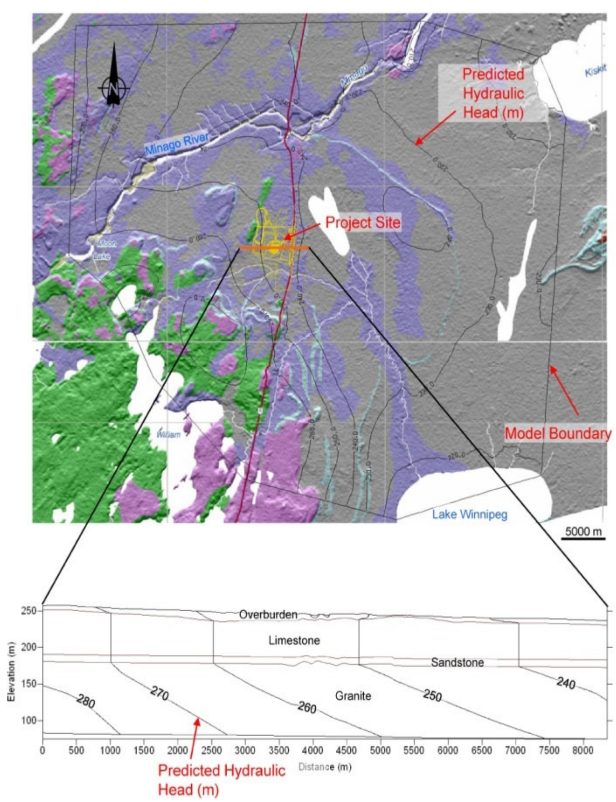


Figure 8. Pre-pumping Conditions in the Limestone Unit (Surficial Geology Map by Matile and Keller, 2006)

The calibrated groundwater model was used to simulate the pumping wells that will be necessary for dewatering of the limestone and sandstone units. The numerical model were used to estimate the number, location, and pumping rates for these wells, and the total pumping rate for the entire wellfield. Based on this analysis, typical well installation schematics were developed and recommendations were provided with respect to the observation well network that will be required to monitor the dewatering progress during mine pit development.

3.3 Mine Dewatering Predictions and Uncertainty

Prior to the full-scale dewatering simulations, preliminary model simulations were conducted to assess the approximate amount of time required for the dewatering to occur once pumping is started. These preliminary simulations, together with the observations gathered during the 5-day pumping test, indicated that limestone dewatering is relatively rapid and that the cone of depression created by dewatering would reach a near-steady state configuration within several months after the full dewatering system is implemented. This relatively rapid response to pumping is primarily related to the low storage and high transmissive properties of the limestone unit. Consequently, the model simulations representing the full-scale dewatering system were conducted in steady-state mode without considering groundwater storage effects.

Several model runs were completed where the location and number of dewatering wells were varied in an attempt to dewater the limestone unit as much as practicable within the pit area and depressurize the underlying sandstone unit without excessive pumping and/or number of pumping wells. It was not considered practical to attempt full dewatering of the sandstone unit as it is of a lower permeability when compared to limestone; therefore, it would receive steady recharge from the overlying limestone. Nevertheless, depressurization of the sandstone unit was considered to be sufficient because, due to its relatively low hydraulic conductivity it was not considered able to provide significant inflows to the pit. Instead, any localized and minor inflows from sandstone could be mitigated using sub-horizontal drain holes installed from the pit benches.

The dewatering wells considered in the analysis were simulated using specified head boundaries, constrained to allow outflow of groundwater only, that were assigned to model layers representing the limestone and sandstone. It was assumed that pumping from these wells would lower the water level in each well below the limestone/sandstone contact. With drawdown at each pumping well fixed, the model calculated the pumping rate at each well thus allowing rapid evaluation of various dewatering options without constant rate adjustments.

The ultimate configuration of the well field is presented in Figure 9. The dewatering system design consists of 12 new dewatering wells evenly-spaced at a distance of approximately 300 m to 400 m along the crest of the ultimate pit, as close to the ultimate pit crest as reasonably possible, and pumping simultaneously from the limestone and sandstone units. The total pumping rate for the wellfield is predicted to be approximately

40,000 m^3/day, and the average pumping rate for an individual well is estimated at about 3,300 m^3/day. As presented on Figure 9, pumping at these rates is predicted to be sufficient to lower the water table to a depth of 70 m, which is near the sandstone/granite contact. The associated drawdown cone, defined using a 1 m drawdown contour, is predicted to extend laterally in the limestone to a distance of approximately 5,000 m to 6,000 m from the proposed open pit.

To address the inherent uncertainty in the hydrogeologic assessment, a series of sensitivity analyses were conducted such that selected model parameters were varied over their uncertainty ranges, and their influence on the predicted dewatering rates was assessed. These parameters included the hydraulic conductivity of the limestone unit, the hydraulic conductivity of the overburden, and the recharge rate. The results of this analysis suggested that the actual dewatering rate for the entire wellfield could vary from 25,000 m^3/day to 90,000 m^3/day. The parameter that had the greatest effect on the dewatering rates was the hydraulic conductivity of the limestone unit. Other model parameters were found to have a relatively small influence on model predictions.

4 CONCLUSIONS

A four-well, long-duration pumping test program was designed and conducted to evaluate the hydrogeologic properties of the aquifer system at the Minago Project. Piezometric response recorded during the program, together with geological and surface-water data were used to develop a numerical hydrogeologic model of the area near the proposed open pit. Following successful calibration, this model was used to develop the preliminary design of a full-scale dewatering system for the pit. The results of this study indicated that pumping at a combined rate of approximately 40,000 m^3/day from 12 wells located around the perimeter of the proposed pit would be sufficient to dewater the limestone unit along the pit walls. The study also indicated that limestone dewatering would be relatively rapid and that the cone of depression created by dewatering would reach near-steady state within a few months after the full dewatering system is operational. This relatively rapid response to pumping is primarily related to the low storage and high transmissive properties of the limestone.

5 REFERENCES

Betcher, R., Grove G., and Pupp, C., 1995. “Groundwater in Manitoba: Hydrogeology, Quality Concerns”, Management; NHRI Contribution No. CS-93017; Environmental Sciences Division, National Hydrology Research Unit (NHRI), Environment Canada, Saskatoon, Saskatchewan.

Butler, J.J., Jr., 1988. “Pumping Tests in Nonuniform Aquifers - the Radially Symmetric Case”, Journal of Hydrology, vol. 101, pp. 15-30.

Cooper H.H. and C.E. Jacob 1946. A generalized graphical method for evaluating formation constants and summarizing well field history. Am. Geophys. Union Trans. Vol. 27, pp. 526-534.

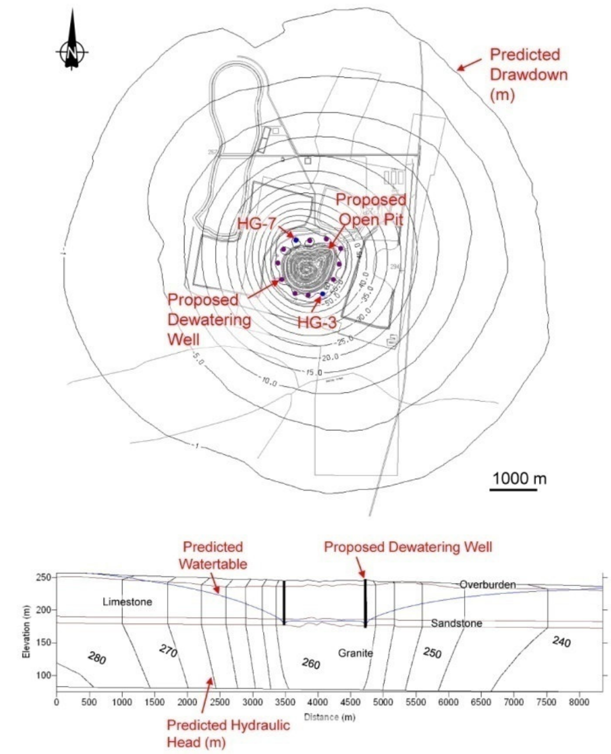


Figure 9. Location of Dewatering Wells and Predicted Full-Scale Dewatering Conditions in the Limestone Unit

Diersch, H.G. 2008. FEFLOW v. 5.3 Finite Element Subsurface Flow and Transport Simulation System. WASY Institute for Water Resources Planning and System Research Ltd., Berlin, Germany.

Doherty, J., L. Bregger, and P. Whyte, 1994. “PEST – Model Independent Parameter Estimation”. Corinda, Australia: Watermark Computing.

Hantush, M.S. and C.E. Jacob, 1955. “Non-steady Radial Flow in an Infinite Leaky Aquifer”, Am. Geophys. Union Trans., vol. 36, pp. 95-100.

Matile, G.L.D., and Keller, G.D., 2006. Surficial geology of the Wekusko Lake map sheet (NTS 63J), Manitoba; Manitoba Science, Technology, Energy, and Mines; Manitoba Geological Survey, Surficial Geology Compilation Map Series SG-63J, scale 1:250 000.

Moench, A.F. and T.A. Prickett, 1972. “Radial flow in an Infinite Aquifer Undergoing Conversion from Artesian to Water-Table Conditions”, Water Resources Research, vol. 8, no. 2, pp. 494-499.

Theis, C.V., 1935. “The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage”, am. geophys. union trans., vol. 16, pp. 519-524.

Walton, W. C., 2008. Technical Commentary on “Upgrading Aquifer Test Analysis”, Groundwater, vol. 46, no. 5, pp. 660-662.