Assessment of feasibility dewatering for Star and Orion South pits and hydrogeological impacts

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ABSTRACT

This paper presents the results of a multiyear hydrogeological study to define the large scale dewatering requirements for the Star-Orion South Diamond Project in Saskatchewan, Canada, and to characterize possible hydrogeological impacts to the shallow groundwater system and surface-water bodies in the vicinity of the project. Two kimberlite pipes penetrate a very transmissive deep regional groundwater system and the proposed pit excavations require implementation of an active dewatering system with a pumping rate up to 120,000 m^3/d. To assess the hydrogeological needs of the Project in support of the Feasibility Dewatering and Environmental Impact Studies the authors developed a numerical groundwater flow model, which was calibrated to water level and pumping test data from numerous hydrogeological wells, including a 20 day pumping test from a prototype dewatering well with a pumping rate of about a 5,450 m^3/d. Model predictions include passive inflow to the proposed pits, the number and locations of required dewatering wells, their respective pumping rates and residual passive inflow to the pits, installation schedule of the dewatering wells, power costs for the proposed dewatering system, propagation of drawdown during proposed dewatering, backfilling of one pit and pit lake infilling of another pit, and the impact of groundwater discharge to the Saskatchewan River and creeks (during both pit excavations and infilling of the pit lake).

INTRODUCTION

The Star-Orion South Diamond Project is located in Saskatchewan, Canada within the Fort a La Corne kimberlite area in complex hydrogeological settings. Two kimberlite pipes penetrate a very transmissive deep regional groundwater system which will be excavated by two propoed pits. Large scale active pit dewatering is required for the project. The purpose of the study was to assess Feasibility Level dewatering requirements and to evaluate possible hydrogeological impacts to the shallow groundwater system and surface-water bodies in the vicinity of the project.

METHODOLOGY

Hydrogeological conditions and completed field work

The hydrogeology of the project area is comprised of two water-bearing systems: a) the very permeable shallow surficial sands, less permeable silts/clays, till, and a basal boulder/gravel unit; and b) the permeable deep sandstones of the Mannville Group and underlying low permeable carbonates of the Souris River Formation. The two water-bearing systems are subdivided by the Colorado shale, a confining layer of very low permeability.

Comprehensive hydrogeological studies were completed from 2005 through 2011 to characterize the shallow and deep groundwater systems and confining unit inbetween. A description of the studies and the results are summarized in Table 1. Locations of completed hydrogeological wells and proposed open pits are shown in Figure 1. Major hydrogeological units are schematically shown in modeled cross section in Figure 2. Their descriptions are given below.

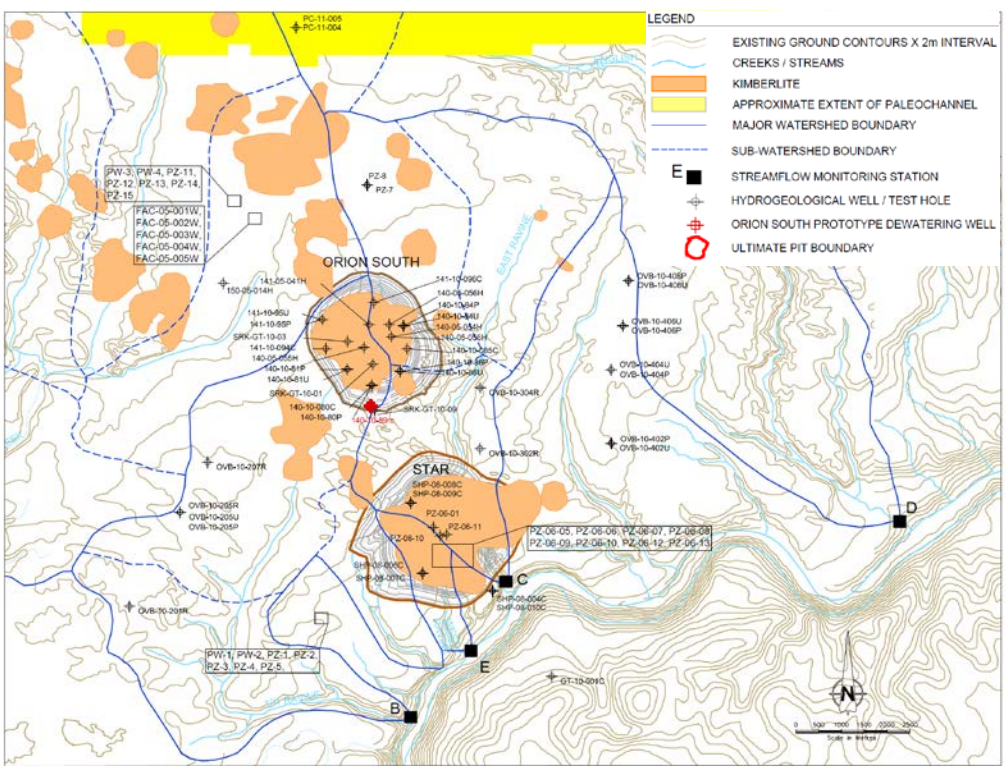


Figure 1 Location of proposed open pits and completed hydrogeological wells

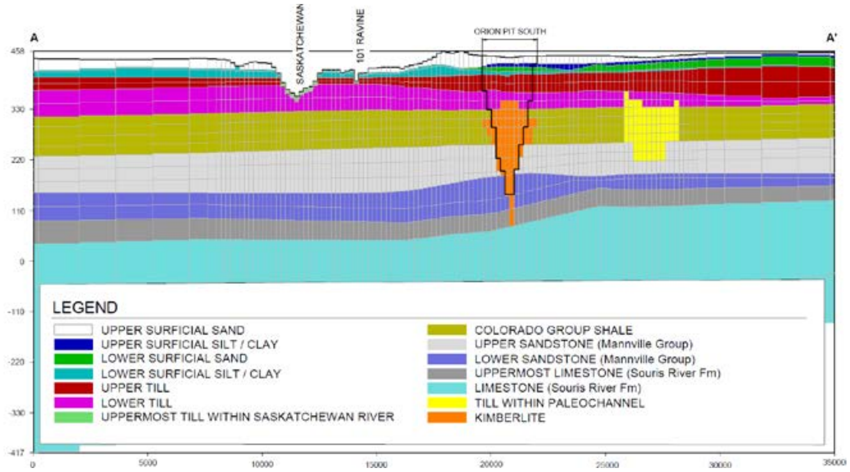


Figure 2 Hydrogeological units incorporated into numerical groundwater model

Table 1 Summary of hydrogeological testing and monitoring well installation

Hydrogeological Unit	**Number of Tests**				**Installed monitoring wells with water level measurements[4]**	**Measured horizontal hydraulic conductivity (m/d)**	
	Short term testing[1]	**Long term pumping test[2]**	**Spinner logging**	**Prototype dewatering pumping test[3]**		**Average**	**Geomean**
Surficial Sand	19	1	-	-	38	12	9
Surficial Silt	5	-	-	-	18	0.06	0.03
Till	20	2	-	-	34	0.14	0.03
Colorado Shale	7	-	-	-	17	0.003	0.0004
Mannville Sandstone	9	2	3	1	21	0.01/3 upper/lower	
Souris River Limestone	1	-	-	-	3	0.01	
Kimberlite	1	-	-	-	8	0.0002	
Total	62	5	3	1	139		

Notes:
[1]Includes airlift, packer injection, and falling head testing.
[2]Duration of three to seven days.
[3]Duration of 20 days.
[4]Includes both standpipes and vibrating wire piezometers

Conceptual hydrogeological model

The conceptual groundwater model of the Fort a la Corne kimberlite area has shallow and deep groundwater systems subdivided by a confining layer.

The most permeable unit within shallow groundwater system is the upper surficial sand with an average thickness of approximately 10m. Sufficial silt/clay, lower sand and till has significantly lower hydraulic conductivity. Infiltration from precipitation recharges the shallow groundwater system. A significant part of this water discharges back into the creeks and ravines through the layer of surficial sand. The deep groundwater system also receives recharge from the shallow groundwater system due to the differences in hydraulic head (from 25m to 45m) and the presence of a vertical downward gradient (shown in Figure 3 below). The Saskatchewan River is a major surface water body within the hydrologic study area, with the river bed located within the lower till. Shallow groundwater discharges into the river during pre-mining conditions flowing from the recharge areas located to the north and south of the river.

The most permeable part of the deep groundwater system is the lower part of the Mannville Group sandstones. Comprehensive hydraulic testing of the Mannville Group was completed using three pumping wells screened across the seven sandstone members with changes in water levels monitored by numerous multilevel piezometers. Two seven day pumping tests and one 20 day pumping test in the prototype dewatering well confirmed high transmissivity of this formation. The spinner logs in all three pumping wells indicate that the lower 30 m to 40 m of the Mannville Group is much more permeable than the remaining upper part and represents a regionally permeable, confined aquifer. Deep groundwater flows from the north to the south with no or very limited hydraulic connection to the river.

The confining layer (Colorado Group) is an approximately 80 m thick sequence of interbedded marine shales and siltstones which overlies the Mannville Group. Kimberlite "fingers" from 3 m to 15 m thick occur within the shale in the vicinity of major kimberlites. The Colorado Group has been locally removed by erosion in the paleochannel located to the north of the Orion South kimberlite (shown in Figures 1 and 2). The Colorado Group has been replaced by fluvial layers of sand and gravel resulting in a possible hydraulic connection between the shallow and deep groundwater systems in this area. The shallow groundwater system may recharge the deep ground water system through the paleochannel.

Kimberlites penetrate the deep groundwater system and confining layer. Two open pits are proposed to excavate the Star and Orion South kimberlite with the ultimate pit bottom elevation within the permeable Mannville aquifer. Passive inflows to the pit would be unmanageable by in-pit sump systems and active dewatering of the deep groundwater system is required to reduce residual passive inflow to the pit.

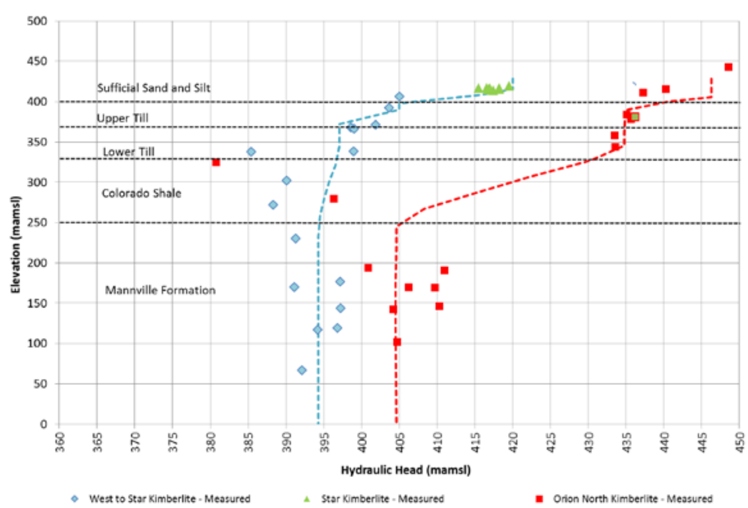


Figure 3 Comparison of measured and modeled water levels vs. elevation for two sites

During mining conditions, the major sources of inflow to the proposed pits and dewatering wells will be:

- Groundwater storage of the shallow groundwater system (during initial stage of pit excavations)
- Groundwater storage of the deep groundwater system (during late stage pit excavations)
- Recharge from direct precipitation
- Inflow from the Saskatchewan River (most likely limited) through the lower till when the hydraulic gradient will be reversed by the Mannville dewatering system
- Recharge to the Mannville Group through the overlying Colorado shale

Numerical groundwater model

A 3-D regional numerical groundwater model was developed using Visual *MODFLOW-SURFACT* code (SWS, 2010 and HGL, 2006). The groundwater model domain encompasses approximately 1,015 square km in the vicinity of the proposed mine, and the finite-difference grid contains 169,920 cells (118 rows and 72 columns) within 20 vertical layers. No-flow model boundaries were chosen at significant distances (from 13.5 to 21 km) from the proposed open pits to reduce the influence of boundaries on simulated drawdown during the mine-dewatering simulations. Additionally, the general head boundary (GHB) conditions (McDonald, M.G. and Harbaugh, A.W., 1988, SWS, 2010) were assigned along the outer model boundaries within the Mannville Group at distances of 50 km (northern and southern) and 35km (western and eastern). The specified heads assigned along these boundaries are based on the water levels in regional monitoring and oil production wells.

The Saskatchewan River and several smaller creeks and ravines (subdivided into 14 stream zones) that regulate groundwater flow within the Star-Orion South project area were incorporated into the numerical groundwater model. The Saskatchewan River, with average yearly flow of about 567m^3/s, is simulated by specified head (cell values applied in the first layer of the model). The specified head cells allow surface water to be hydraulically connected to the groundwater without any restrictions. The other stream zones, with average yearly flow varying from 500 m^3/d to 27,800 m^3/d, are simulated by combinations of drain cells and seepage face cells (RSF4 package of MODFLOW-SURFACT code, HGL, 2006). Drain cells were used to simulate the courses of major creeks and ravines in the vicinities of the proposed pits. Seepage face cells were used to simulate valleys with smaller tributaries and springs.

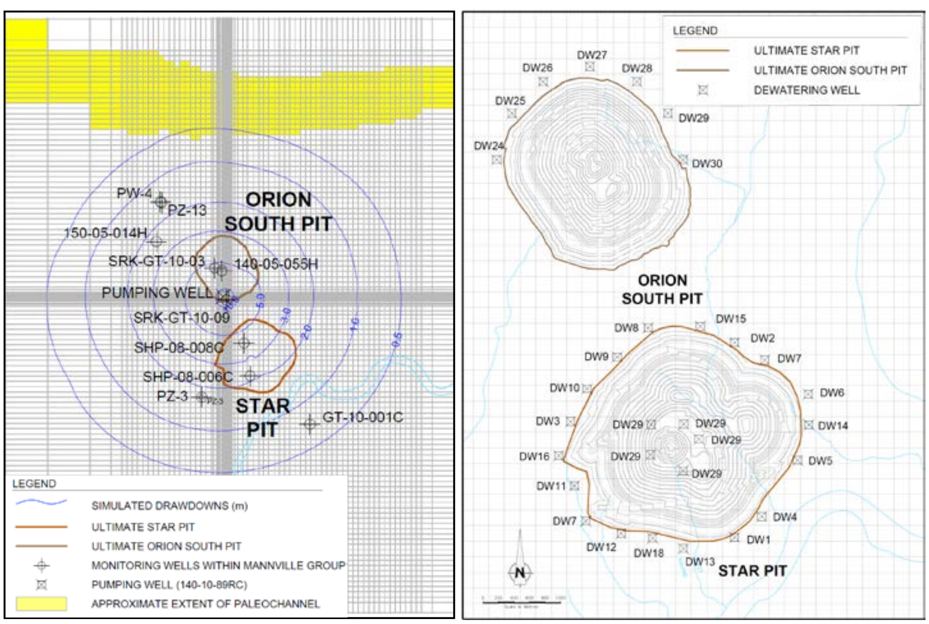
Recharge from precipitation is applied to the first saturated cell (the uppermost active layer) within the model domain by using yearly averaged rates; 20 mm/year and 5 mm/year within the upper surficial sand and silt/clay, lower surficial sand and upper till, respectively. These recharge rates are 4.2% and 1% of average yearly precipitation (468 mm/year).

Hydrogeological units incorporated into the numerical groundwater model are shown in cross section in Figure 2. Calibrated hydraulic parameters of the units are shown in Table 2.

The model was calibrated to measured pre-mining steady state water levels in 139 monitoring wells and to transient conditions observed during the 20 day pumping test from the prototype dewatering well installed within the Mannville Formation. Examples of calibration results are presented in Figure 3, which shows a comparison of measured and simulated vertical hydraulic gradients at two sites under pre-mining steady state conditions and Figure 4a, which shows simulated drawdown at the end of the 20 day pumping test, indicating that drawdown propagates below the Saskatchewan river, as was observed in the field.

Table 2 Hydraulic parameters used in numerical groundwater model

	Hydrogeologic Unit	Hydraulic Conductivity (m/d) Kh	Kv	Anisotropy Ratio	Specific Storage Ss (1/m)	Specific Yield Sy ()
Shallow Groundwater System	Upper Surficial Sand	10	10	1	1.00E-06	0.2
	Upper Surficial Silt/Clay	0.05	0.0005	100	1.00E-04	0.15
	Lower Surficial Sand	0.1	0.01	10	1.00E-04	0.15
	Lower Surficial Silt/Clay	0.03	1.00E-04	300	1.00E-04	0.15
	Uppermost Till within River Valley	0.03	1.00E-04	300	1.00E-04	0.1
	Upper Till	0.018	6.00E-05	300	1.00E-04	0.1
	Lower Till	0.018	6.00E-05	300	1.00E-04	0.1
	Lower Till Underlying River Valley	0.1	0.001	100	1.00E-04	0.1
	Till within Paleochannel	0.018	6.00E-05	300	1.00E-05	0.1
	Paleochannel (lower part)	0.1	0.001	100	1.00E-05	0.1
Confining Layer	Kimberlite	2.00E-04	2.00E-04	1	1.00E-06	0.01
	Colorado Group Shale	4.00E-04	6.00E-05	7	1.00E-05	0.01
Deep Groundwater System	Sandstone (Upper part of Mannville Fm)	0.01	0.00033	30	3.00E-06	0.02
	Sandstone (Lower part of Mannville Fm)	3	0.1	30	3.00E-06	0.02
	Uppermost Limestone (Souris River Fm)	0.01	0.001	10	1.00E-06	0.01
	Limestone (Souris River Fm)	0.001	0.0001	10	1.00E-06	0.005
	Backfill Material in Star Pit	0.01	0.01	1	5.00E-06	0.03



a) b)

Figure 4 (a) Drawdown at the end of pumping test and (b) location of simulated dewatering wells

Results of the model calibration reasonably reproduce the observed vertical hydraulic gradient between the shallow and deep groundwater systems and changes in water levels within the Mannvile Formation as observed during the long-term pumping test.

The calibrated model was used for predicting dewatering requirements and pit lake infilling during post-mining conditions. 2,013 drain cells were incorporated into the model with a variable in time elevations corresponding to the yearly pit shells (ultimate pit shels are shown in Figure 4b). The Star pit will be excavated first. Excavation of the Orion South pit will start in Year 10 and continue through Year 17, when both pits will be excavated simultaneously. Excavation of the Orion South pit will then continue through Year 24 while the Star pit will be backfilled starting in Year 18. Minimum pit bottom elevations vs. time are shown in Figure 5. Elevation of the ultimate bottom of the Star and Orion pits are 100 mamsl and 145 mamsl, respectively (depths of pits are 320 m and 295 m).

Simulation of dewatering wells

The groundwater flow model simulates dewatering wells installed into the Mannville sandstone as "pumping centers" or cells within the finite-difference grid at which a specified amount of water is withdrawn or a specified water level is maintained by removing water. A total of 30 such pumping centers were simulated with locations shown in Figure 4b. Each pumping center was simulated by a vertical column of cells numerically linked together by applying high vertical hydraulic conductivity, allowing simulation of the same water level within the linked vertical cells.

It should be noted that there is a naturally occurring limiting factor for the effectiveness of the dewatering system at the proposed Star pit. This factor is the presence of the relatively tight limestone unit at the base of the permeable Mannville sandstone. The ultimate bottom of the proposed Star pit will be only about 15 m above the bottom of this unit. The lower K of the limestone will diminish the potential hydraulic efficiency of the dewatering wells during later pit life, since it limits the available drawdown. Thus, in order to realistically simulate conventional dewatering wells in the numerical model, an assumption was made regarding the amount of "freeboard" that will occur in a well. Freeboard is the saturated thickness of the sandstone immediately adjacent to the wellbore that cannot be dewatered due to well inefficiencies (or "well losses") and natural hydraulic limits such as the formation of a seepage face on the wellbore surface. Considering that the lower part of the Mannville sandstone contains the most transmissivity, it was assumed that the freeboard in the dewatering wells around the proposed pit will be about 30 m. A slightly smaller freeboard of 20 m was used for the Star in-pit dewatering wells. The ultimate bottom of the proposed Orion South Pit will be about 34 m above the bottom of the Mannville sandstone and dewatering wells will not have a limiting factor like the Star pit.

Groundwater withdrawal by dewatering wells is simulated with a constant pumping rate (Qw=5,450 m^3/d –pumping rate achieved by prototype dewatering well) until water levels in the wells are above the freeboard elevation. Pumping rates were switched to drain cell fluxes when water levels in the pumping wells reached freeboard elevations. To account for well interaction and to avoid injecting water instead of pumping, drain cell fluxes were switched to Qw=0 when water levels were below the specified freeboard elevation.

RESULTS AND DISCUSSION

Predictions of dewatering requirements

The groundwater-flow model was used to make predictive simulations of a) passive inflow to the proposed pits, b) dewatering requirements and residual passive inflows, c) propagation of drawdown during proposed dewatering, d) pit lake infilling; and e) impacts of groundwater discharge to the creeks and Saskatchewan River (during both pit excavation and pit lake infilling).

Predictive numerical simulations were conducted for both passive inflow conditions (i.e., no dewatering) and for conditions with an active dewatering system. Passive inflow is the amount of ground water that will enter the excavation without implementation of any active dewatering system (e.g., pumping wells, drainholes, etc.) to intercept some or all of the water. The amount of water that still enters an excavation after active dewatering is implemented is referred to as residual passive inflow (RPI). Generally, the goal of an active dewatering system is to reduce RPI to an amount that is inconsequential relative to the mining operations.

The predicted passive inflows to the proposed Star and Orion South pit over the life of the mine, with no active dewatering, are shown on Figure 5. The numerical simulations predict that the maximum passive inflow will be about 78,600 m^3/d for the Star and 17,800 m^3/d for the Orion South pits at the end of their excavations.

It was concluded that passive inflow to the pits cannot be managed by an in-pit sump dewatering system therefore active dewatering was simulated with dewatering wells installed within the Mannville sandstone.

Active dewatering predictions for both the proposed Star and Orion South pits indicate:

- Eighteen dewatering wells on the Star perimeter will be required to operate from Year 5, when necessary power will be available on the site, through Year 17 (end of excavation of the Star pit). These 18 perimeter wells need to be in operation to dewater the Orion South pit through Year 24 (end of mine life).
- Five in-pit dewatering wells are required within the Star pit at lower benches and need to be in operation from Year 15 through Year 17 to minimize residual passive inflow when the pit will be excavated within the permeable part of Lower Mannville sandstone. These in-pit dewatering wells should operate through Year 19 during the initial stage of backfilling of the Star pit.
- Seven Orion South perimeter wells will be required to operate from Year 19 through Year 24 in addition to the 18 Star perimeter dewatering wells. These wells should be drilled at the northern extent of the Orion South pit and intercept additional groundwater from the shallow hydrogeological system if some leakage through the paleochannel occurs.
- Total pumping from the dewatering wells of as much as 98,100 m^3/d for the Star and 120,000 m^3/d for the Orion South pits. The latter value includes total pumping rates from continuing pumping of Star wells plus up to 38,200 m^3/d from additional Orion South dewatering wells.
- RPI of up to 18,700 m^3/d for the Star and 15,200 m^3/d for the Orion South, will occur when pit bottom elevations are above the top of the Mannville Group; most of this inflow will occur from the surficial sand at the beginning of the excavations or from the major "push-backs" at the ground surface. RPI from the Mannville sandstone is predicted to be 3,000 m^3/d and 2,000 m^3/d for the Star and Orion South, respectively, during excavation of their deepest parts.

Power cost was estimated Based on predicted dewatering requirements for the Mannvile pumping system used to dewater the Star and Orion South pits.

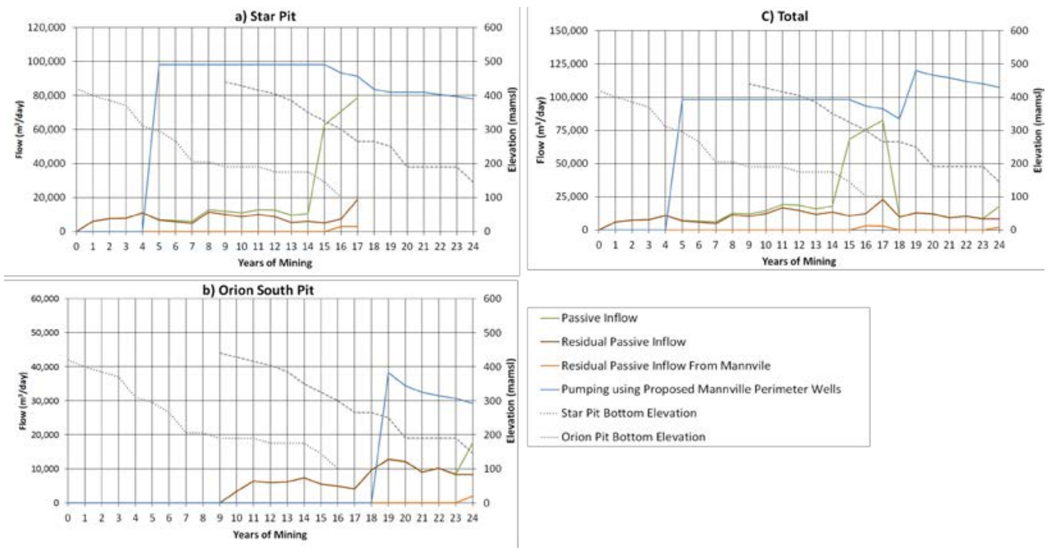


Figure 5 Predicted dewatering requirements (base case)

The model predicts that significant drawdown, from 70 m to 250 m, will occur within the Mannville Group. This will cause an extensive cone of drawdown to propagate within the shallow groundwater system, due to increasing vertical recharge through the Colorado Group shale as well as where the shale was eroded by the paleochannel. The model predicts that the 1m contour of drawdown within the uppermost surficial sand will propagate to a maximum distance of 4 km to 7 km to the west, to the east, and to the north from both pits, and will be limited by the Saskatchewan River to the south.

Pit dewatering will reduce groundwater discharge to the creeks and ravines in the project area.

The Orion South pit lake will form after mining ceases. It will take about 315 years for groundwater to fill in the pit lake to a level of 95%. It will take more than 350 years to reach new steady state post-mining conditions with pit lake water levels predicted to be 406 mamsl (or about 30 m below pre-mining water table). Formation of the Orion South pit lake, hydraulically connecting the shallow and deep groundwater systems, will change water levels within the upper surficial sand during long-term post-mining conditions. The extent of the 1m contour of drawdown within the upper saturated layer of the model will propagate at a distance of to 2 to 3 km, and will stay there in perpetuity. The model also predicts small but permanent impacts to the creeks and ravines compared to pre-mining conditions.

Results of Sensitivity Analysis

The comprehensive sensitivity analysis was conducted to define the effects of key hydrogeological parameters on dewatering requirements and potential impacts to the shallow groundwater system. These runs include a) increases/decreases of vertical hydraulic conductivity of the Colorado shale, till, and silt, and b) replacement of GHB conditions within the Mannville sandstone by no-flow boundary conditions during predictive simulation. Results of completed modeling of predicted dewatering requirements are shown in Figure 6 and indicate:

- Increasing vertical hydraulic conductivity of the Colorado Group shale and lower till by a factor of 3 will increase recharge to the deep groundwater system from the shallow system, and as a result, the model predicts increasing total average dewatering rate by a factor of about 1.1 and propagation of drawdown within the shallow groundwater system almost to the edge of model domain.

- Decreasing vertical hydraulic conductivity of the Colorado shale and lower till by a factor of 3 will significantly decrease recharge to the deep groundwater system from the shallow system, and as a result the model predicts decreasing total average dewatering rate by a factor of about 1.05 and very limited propagation of drawdown within the shallow groundwater system.
- Replacing GHB conditions along the model domain within the Mannville Group by no-flow conditions will slightly increase recharge of the deep groundwater system from the shallow system, and as a result the model predicts that the total average dewatering rate will not have a significant change and intermediate propagation of drawdown will occur within the shallow groundwater system (similarly to the Base Case with more drawdown along the paleochannel).

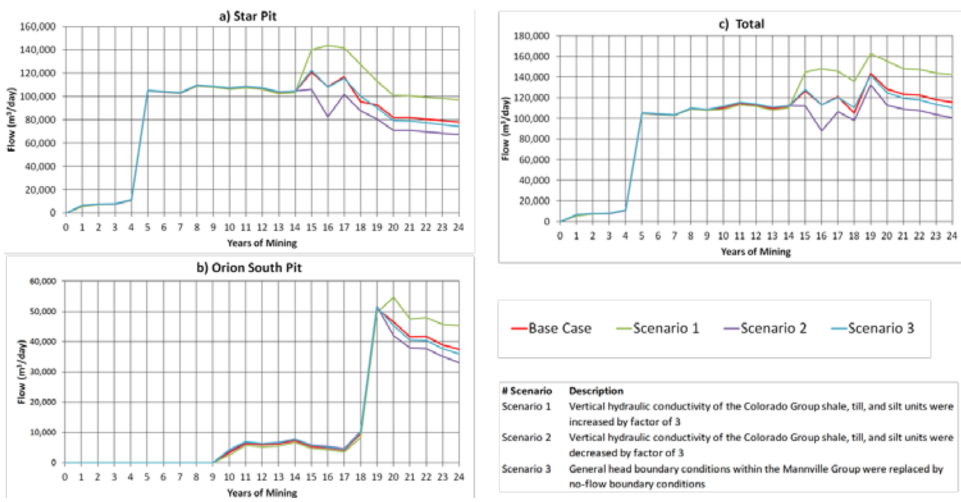


Figure 6 Results of sensitivity analysis of hydrogeological parameters on predicted dewatering

CONCLUSIONS

Completed hydrogeological studies, numerical groundwater modelling, and assessment of dewatering requirements for Star and Orion South Pits, and evaluation of hydrogeological impacts were used to support the Feasibility and Permitting Studies for the project.

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