Modeling of Dewatering & Depressurization of an Open Pit with Historic Underground Mine Workings

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SUMMARY

This paper presents a case study of three-dimensional groundwater modeling of a proposed open pit at a gold mine project with historic flooded underground (u/g) mine workings in British Columbia, Canada. The modelling approach for dewatering the open pit included passive dewatering by draining water under natural hydraulic gradients and active dewatering by using active dewater wells, together with residual water drains. Target water level drawdowns behind the pit wall were used to determine the number and depths of dewatering wells to meet the slope stability requirements and in estimation of pit inflow rates. Conceptualizing the u/g mine workings and assigning appropriate flow boundary conditions throughout the life of the mine posed some unique challenges. Initially the flow boundary conditions for the underground workings were applied as drain boundaries with constant head at a pre-existing managed level. Subsequently, the boundary conditions had to be adjusted as mining progressed to reflect the likely management of mine water as the open pit mining progresses. Artificial observation wells were assigned together with dewatering wells to ensure that the required drawdown targets were met. The modelling approach and key inputs/outputs as well as lessons learned are presented.

Keywords: Groundwater Modeling, Open Pit, Dewatering, Depressurization, Underground Mine Workings

1. Introduction

Mining natural resources such as metallic ores and coal often causes significant impacts on groundwater and its interactions with surface water, and groundwater and surface water contaminations. Therefore, comprehensive studies including extensive baseline characterization and model predictions of potential mine impacts are required by regulators around the world in project approval and permitting processes for protection of environment and public interests.

From the engineering perspective, mining can be conducted with two approaches: underground (u/g) mining, and open pit excavation. Mine dewatering can be achieved with two methods: actively dewatering using pumping wells, and passively dewatering using drain galleries. Estimation of groundwater flow into an open pit, u/g mine workings, as well as depressurization analysis, are import tasks for mine dewatering and stability designs for safety. Such work can be done using analytical or numerical groundwater models depending on mine phases (e.g., preliminary economic assessment, prefeasibility, feasibility) and availability of information.

The case study presented here was conducted for a large gold mine revitalization project located in British Columbia (BC), Canada. The ore was mined historically with the u/g mine method, and the mine is proposed to be revitalized by expanding the historic u/g mine workings with open pits.

In this study, a conceptual hydrogeological model (CHM) was developed based on a geological model to represent the groundwater flow system at the existing baseline (pre-mining) conditions with the proposed open-pit and the historic u/g mine workings. A three-dimensional (3D) numerical groundwater model was developed to align with the CHM and was used for the mine dewatering simulations.

The objectives of this study included to estimate the quantity of groundwater flow into the pit and the u/g mine workings, and to predict active dewatering wells to be required for depressurization of the pit wall to meet the target groundwater level drawdowns, in support of the pit slope stability analysis and the project feasibility designs.

This paper presents a summary of the CHM; the numerical model approaches, some key inputs and outputs at the pre-mining, the predicted groundwater flow quantities into the open pit, and the estimated number of active dewater wells (for satisfaction of the pit wall depressurization), as well as lesson learned from the groundwater modeling exercise.

2. Conceptual Hydro/geological Model

2.1. Geological Model

A conceptual geological model was first developed through the proposed pit and existing u/g mine workings (Figure 2.1), based on the regional / local geological information and drilling lithological logging data.

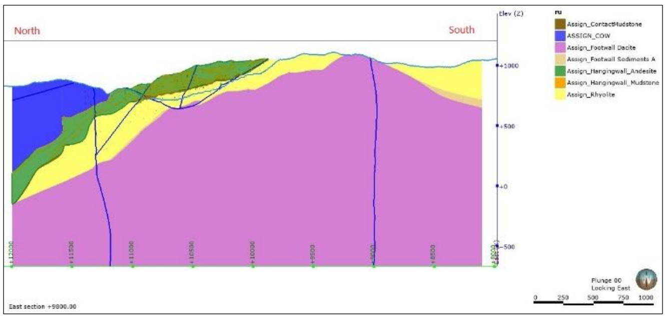

Figure 2.1 Conceptual Geological Model

The geological information shows overburden distribution is limited at the site. The bedrock comprises folded and faulted volcanic and sedimentary sequences called the Hazelton and Bowser Groups. The stratigraphic sequence is subdivided into the Lower Footwall (consisting of rhyolite and dacite, yellow and purple colors in Figure 2.1), the Hanging Wall (consisting of andesite and mudstone, green color in Figure 2.1), and Contact Mudstone between the lower and hanging walls. The ore zones are primarily hosted within an anticline structure at the contact between the rhyolite and overlying contact mudstone. The historic underground mine workings are located beneath an anticline ridge. The Project area is highly faulted, with some large faults interpreted with steeply dipping, sub-parallel and northeast-southwest trending.

2.2. Hydrogeological Model

A conceptual hydrogeological model (CHM) was developed (Figure 2.2), to represent the groundwater system at the site, which is predominantly unconfined and composed of bedrock, with limited overburden, based on the geological model and the hydrogeological data, including measured groundwater levels and tested bedrock hydraulic conductivities (K).

The project site is in rocky mountainous terrain with topographic elevations varying from 307 to 1,759 masl. The surface topography can be expected to have a pervasive influence on the underlying mountain groundwater flow system (Forster and Smith, 1988).

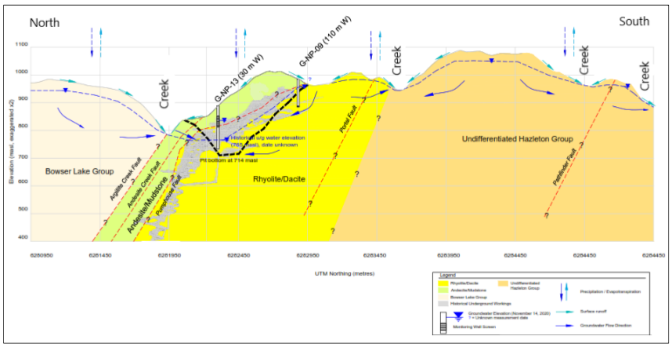

Figure 2.2 Conceptual Hydrogeological Model

The aquifer at the site receives recharge from precipitation and infiltration of surface runoff, and groundwater flow from upper slopes; and it discharges water through evapotranspiration and into the downstream receiving creeks.

Hydrostratigraphically, the proposed open pit and the historic u/g mine is within the bedrock aquifer, consisting of the andesite/mudstone unit in the Hanging Wall of the anticline (green color in Figure 2.2) and the rhyolite/dacite unit in the Footwall of the anticline (yellow and brown colors in Figure 2.2), as well as faults, one of which was characterized as a highly permeable and water-bearing structure. The joints in the rock mass were believed to allow rapid infiltration of precipitation (up to 50% of mean annual precipitation, or over 1,000 mm/year as recharge) into the u/g mine in high flow seasons.

The tested data indicates that the Hanging Wall andesite and mudstone is more permeable than the Footwall rhyolite (Figure 2.3). The bedrock (andesite, mudstone, rhyolite) at shallow depths (< 50 mbgs) are generally more permeable than those at greater depths (Figure 2.4). Bedrock permeability is expected to have a trend of decreasing with depth, despite the limited data does not show such a relationship.

The historic u/g mine workings are considered as a distinct hydraulic property zone with elevated permeability, transmissivity, and storage. It could receive high infiltration from precipitation due to potential subsidence and surface cracks. Groundwater levels in the u/g mine has been managed by pumping with water level controlled at 765 masl, therefore it likely behaves as a local groundwater sink. The proposed open pit at dewatering is also expected to be a groundwater sink.

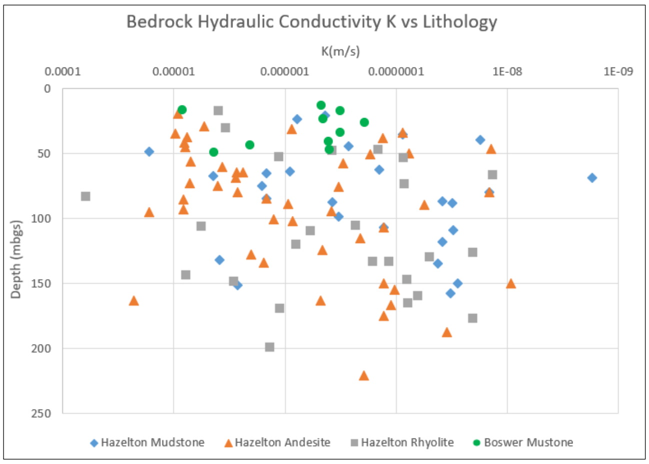

Figure 2.3 Bedrock Hydraulic Conductivity vs. Rock Types

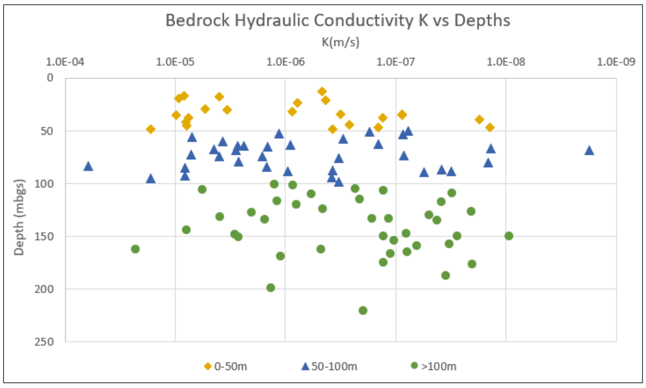

Figure 2.4 Bedrock Hydraulic Conductivity vs. Depths

3. Pre-mining Model

3.1. Model Calibration

A pre-mining numerical model was developed using the software – the Groundwater Vistas version 7.24, Build 260 (ESI 2017), plus the MODFLOW-SURFACT Flow version 4.0 (HGL 1996), and by following the relevant groundwater modeling guidelines for assessing impacts of proposed natural resource development activities (BC MOE 2012). The model domain is 9 km (north to south) by 11 km (west to east). It contains 8 layers (with thickness increasing from 20 m to 276 m), 257 rows and 249 columns, and 25 m x 25 m grids in the mine zone.

The flow boundaries assigned include:

- Constant head boundaries for lakes
- River boundaries for rivers and creeks
- Drain boundaries for small streams
- Drain boundary for the u/g workings.

The pre-mining model includes five recharge zones delineated according to the topographic elevations (e.g., the orographic effects), together with the u/g mine zone, and the calibrated recharge rates vary from 9% to 37% of the mean annual precipitation (2,700 mm/year) estimated at the site (Table 3.1).

Table 3.1 Calibrated Recharge at Pre-mining

Zone	Topo Elevation (masl)	Recharge (mm/year)	% of Mean Annual Precipitation
1	< 600	254	9
2	600-900	338	13
3	900-1,200	423	16
4	> 1,200	423	16
5	U/G Mine Zone	1,000	37

A total of 16 hydrostratigraphic units (HSU) were assigned according to the conceptual geological and hydrogeological models, together with the information including the bedrock geology (Figure 3.1 for Layer 1). The calibrated hydraulic conductivities (K) are presented in Table 3.2, based on the tested data as well as assumed (for deeper bedrock and overburden).

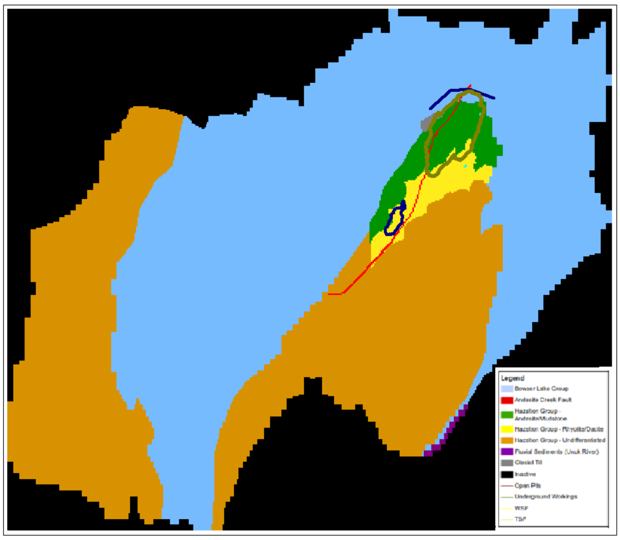

Figure 3.1 Pre-mining Model HSUs

Table 3.2 Pre-mining Model Calibrated K Values

Hydrostratigraphic Unit			K	Model Layer
Unit	Name	HSU	m/s	
Upper Bedrock	Bowser Lake Group	1	5.0E-07	L1-L4
	Faults	2	1.0E-05	L1-L4
	Andesite/Mudstone	3	5.0E-07	L1-L4
	Rhyolite/Dacite	4	1.0E-08	L1-L4
	Undifferentiated Rocks	5	7.5E-07	L1-L4
Middle Bedrock	Bowser Lake Group	6	5.0E-08	L5-L6
	Andesite Creek Fault	7	1.0E-05	L5-L6
	Andesite/Mudstone	8	1.0E-07	L5-L6
	Rhyolite/Dacite	9	5.0E-09	L5-L6
	Undifferentiated Rocks	10	7.5E-08	L5-L6
Lower Bedrock	Bowser Lake Group	11	5.0E-09	L7-L8
	Rhyolite/Dacite	12	2.0E-09	L7-L8
	Undifferentiated Rocks	13	7.5E-09	L7-L8
U/G Mine	Backfilled U/G Mine	14	1.0E-06	L1-L7
Overburden	Fluvial Sediments	15	1.0E-05	L1-L2
	Glacial Till	16	1.0E-07	L1

The model was calibrated to three targets including:

- Measured groundwater levels / hydraulic heads in 19 monitoring wells / piezometers (Figure 3.2) with a normalized root of mean

square (NRMS) of 4.9% and a residual mean of -0.9 m
- Observed stream low flows (Table 3.3)
- U/G Mine Pump Water Measurements (Table 3.3).

Generally, a NRMS is <10% is considered as a good calibration and <5% is a very good calibration (BC MOE 2012, Barnett, et al 2012, NBLM 2006, NBMRR 2021). The results demonstrate that this model is well calibrated with good quality, and therefore it is reliable for predictions.

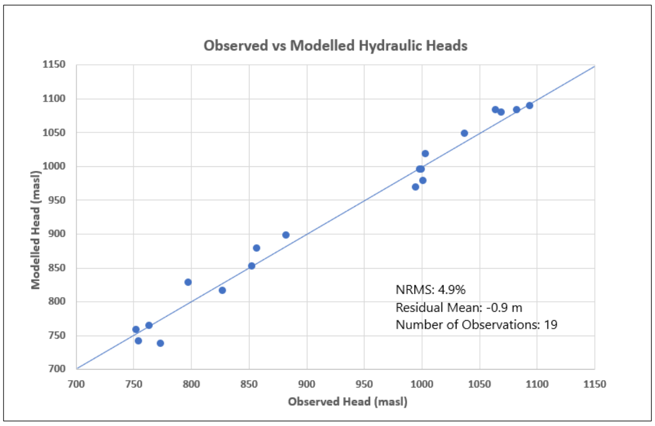

Figure 3.2 Baseline Model Head Calibration

Table 3.3 Calibrations to Stream Flows & U/G Mine Water Pumping Rates

Name	Modelled GW Discharge	Observed Stream Flow / U/G Mine Pump Water
Creek 1	0.27 m^3/s	0.17 m^3/s (Annual 7-Day Low Flow), 0.34 m^3/s (Summer 7-day Low Flow, Jun-Sept) in 2020; 0.27 m^3/s (Annual 7-Day Low Flow), 0.66 m^3/s (Summer 7-day Low Flow, Jun-Sept) in 2021
Creek 2	0.12 m^3/s	~ ½ of Creek 1
U/G Mine	441 gpm	420 gpm (Pump 1), 525 gpm (average of two pumps)

3.2. Simulated Pre-mining Flow

The simulated stead-state hydraulic head contours (Figure 3.3), representing the long-term average, indicate that groundwater flow patterns at the site are generally mimic the surface topography and flow directions are from high ground (recharge zone) to lower elevations (discharge zone). The proposed mine zone (the polygon/polylines in the northeast area of the model domain) receives groundwater recharge from high ground and discharges into the nearby creeks. The results align up with the CHM.

Sensitivity analysis indicated that the model calibration and simulation results are highly sensitive to the key input parameters (recharge and K).

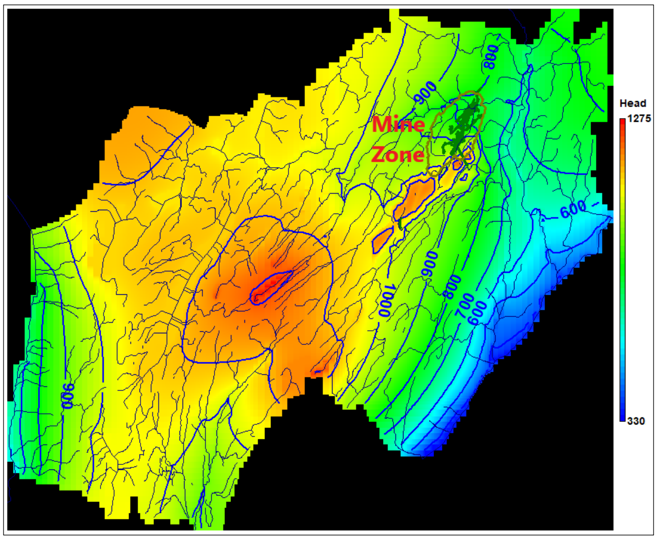

Figure 3.3 Simulated Pre-mining Head Contours

4. Pit Dewatering / Depressurization Model

4.1. Methodology

A predictive model was constructed using the calibrated pre-mining model to simulate dewatering of the open pit at its maximum extent to meet water level drawdown targets (0 to 40 m behind the pit wall) required for depressurization (Figure 4.1), to support pit slope stability analysis. Two dewatering methods were adopted: active dewatering, and passive dewatering.

The active dewatering was implemented by assigning a series of attentive vertical dewater wells (38 in total), including 17 wells along the pit perimeter (called perimeter wells) and 21 wells inside the pit (called in-pit wells). The space between the neighboring wells was specified 200 m (Figure 4.1), and the depths of the perimeter wells were set down to the pit bottom along the rows, and the depths of the in-pit wells were set to the target drawdowns. The bottom of each well (e.g., at pump in-take) was assigned with a drain cell elevation at the target water level. The wells were assumed to be screened along the entire depths.

The passive dewatering was implemented by assigning drain cells in the entire pit to represent the passive drainage of water such as with horizontal drillholes or drain galleries.

In addition, a series of artificial observation wells were assigned in between the dewater wells (Figure 4.1), for the purpose to examine and ensure the model calculated water level behind the pit wall meets the drawdown targets for depressurization.

Furthermore, zero recharge was assumed within the pit footprint, by assuming that precipitation falling into the pit will be collected and transferred away.

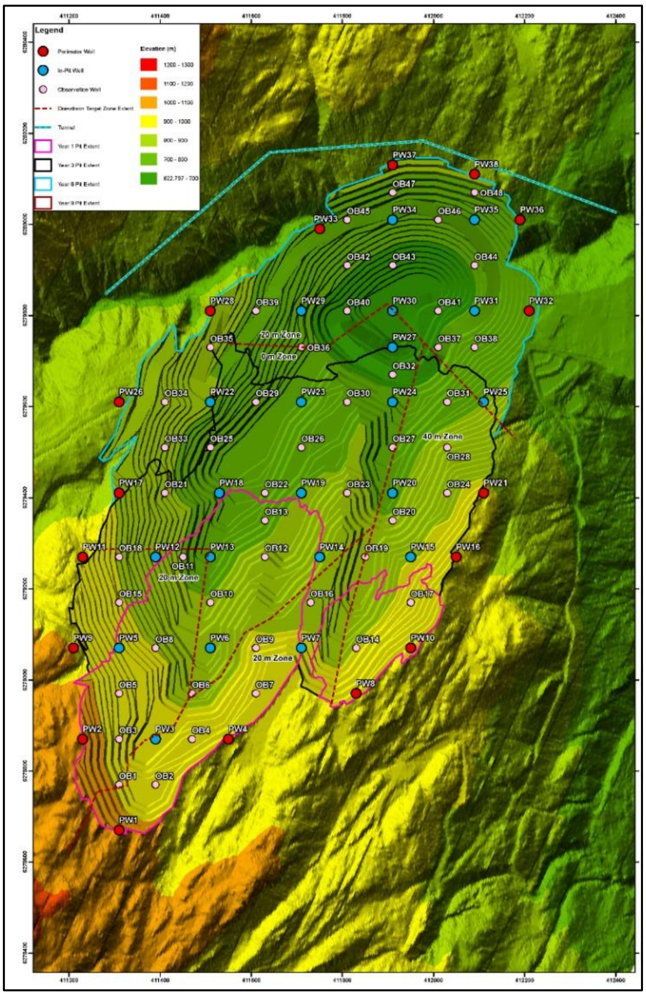

Figure 4.1 Layout of Dewater and Observation Wells Assigned Initially for Pit Depressurization

4.2. Base Case Results

The Base Case results from steady-state simulation (representing long-term average) are shown in Figure 4.2 for the active dewater wells (8 perimeter wells and 6 in-pit wells) to be required in satisfaction with the depressurization drawdown targets. The model calculated no or negligible groundwater flow to be captured in the other 24 wells initially assigned. The fundamental reason behind is that the proposed pit is located at the top of ridge (with deep groundwater level).

The model simulated phreatic surface (the aqua color line) behind the pit wall (through the deepest pit bottom center) is shown in Figure 4.3 (for longitudinal cross-section from southwest to northeast), and Figure 4.4 (for transverse cross-section from northwest to southeast).

The calculated of dewater wells, depths, well inflow, and residual flow into the passive drains in the pit, as well as the u/g mine inflow, are presented in Table 4.1. The open pit will be excavated into the u/g mine workings, and dewatering of the pit is predicted to reduce groundwater flow into the u/g mine workings (to 20 L/s, in comparison with the pre-mining 441 gpm or 28 L/s).

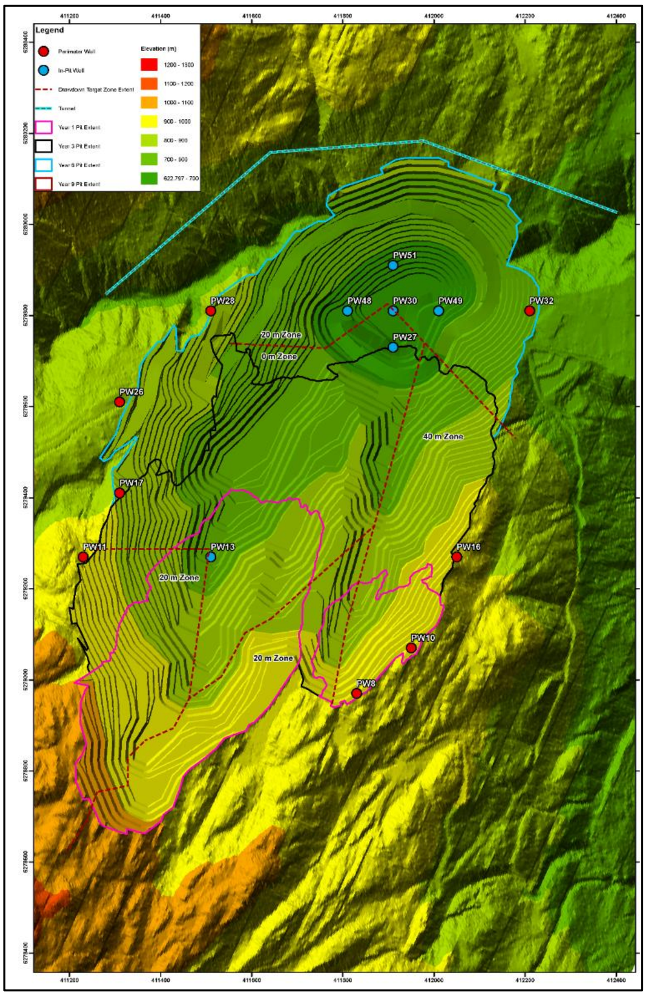

Figure 4.2 Locations of Dewater Wells Required for Pit Depressurization

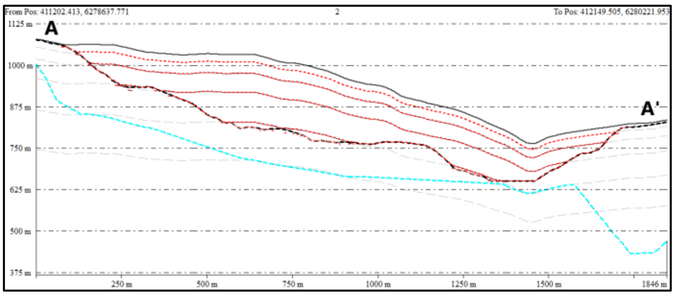

Figure 4.3 Simulated Phreatic Surface along Longitudinal Cross-section through the Pit Bottom

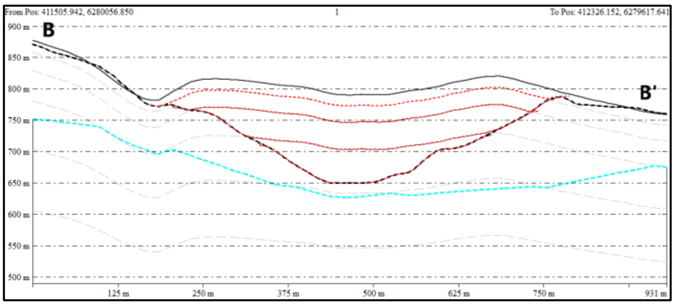

Figure 4.4 Simulated Phreatic Surface along Transverse Cross-section through the Pit Bottom

Table 4.1 Pit Dewatering Base Case Results

Pit Dewater Wells / Depths	Total Well Inflow (L/s)	Residual Pit Inflow (L/s)	U/G Mine Inflow (L/s)
14 wells with depth of 1,936 m in total	62	2	20

4.2. Sensitivities

Four sensitivity scenarios were simulated for the pit dewatering model, to examine uncertainties in the predicted number of dewater wells and the flow rates, associated with the key parameters (recharge and K).

- Sensitivity 1: Wet – 30% more recharge than the pre-mining
- Sensitivity 2: Dry – 30% less recharge than the pre-mining
- Sensitivity 3: K x 5 – the K values increased by 5 times from the pre-mining
- Sensitivity 4: K / 5 – the K values decreased by 5 times from the pre-mining

The results (Table 4.2) show that in comparison with the pre-mining, more inflow was predicted (hence more wells to be required) in the wet and higher K cases, and less inflow (fewer wells) in the dry and lower K cases.

High uncertainties exist in the predictions, as expected due to the complexities in climate and geology.

Table 4.2 Pit Dewatering Sensitivity Results

Inflow (L/s)	Base Case	Wet	Dry	K x 5	K / 5
Dewater Well Inflow	62	66	56	187	23
Residual Pit Inflow	2	2	1	5	2
# of Dewater Wells	14	17	13	11	21

5. Summary

This modeling study for dewatering of an open pit proposed with a historical u/g mine workings beneath was conducted using a 3D groundwater model, which was developed based on conceptual geological / hydrogeological models.

The results above were used by engineers for the pit wall stability analysis, the mine water management designs, and financial analysis.

The following lessons were learned from the study:

- Whenever possible, a model should be calibrated with multiple targets including not only measured groundwater levels, but also observed stream flows, and available mine management water flow, in addition to do qualitative comparations of model simulated to field observed (such as groundwater seepage spots) and examine the global mass balance (<1%). Good quality of calibrations is a key defensibility of a model with regulators.
- The approach adopted in this study with active dewater wells assigned with drain boundaries at the well bottom allows the model to predict groundwater flow into the wells based on hydraulic gradients and hydraulic parameters (e.g., K), rather than specifying well pumping rates *a priori*. The latter approach may cause excessive water to be extracted, resulting in more costs for mine water management.
- The existing u/g mine workings makes the pit dewatering/depressurization modeling much more complicated. One of the challenges encountered during this modeling was about how to deal with the u/g mine workings and to assign the drain boundary to present the workings appropriately in the mine operation. What we did was to assign the drain boundary to represent the historic u/g mine with the managed water level at the pre-mining conditions but removed the u/g mine drain cells within the pit shell and replaced the drain elevations in the u/g mine cells below the pit with their actual elevations.

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Professional profile

Yaming Chen obtained his Ph.D. degree in hydrogeology from the University of British Columbia in Canada with specialization in modeling of groundwater and coupled surface water flow and transport in porous and fractured media. He has over 35 years of experience in physical and contaminant hydrogeology on mine projects around the world. His expertise covers baseline studies, environmental impact assessment and permitting, resource assessments and monitoring, and expert review. He specializes in groundwater flow and contaminant transport modeling for mining and other resource development projects.

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Professional profile

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