Adit Dewatering at a Proposed Gold Mine: Numerical Analysis of a Large-Scale Long-Term Pumping Test

Dawn Paszkowski[1], Carl Mendoza[1], Trevor Crozier[1], Max Holtby[2]

[1]*BGC Engineering Inc., 500-980 Howe St., Vancouver, British Columbia, Canada, V6Z 0C8*
DPaszkowski@bgcengineering.ca, CMendoza@bgcengineering.ca, TCrozier@bgcengineering.ca
[2]*Pretium Resources Inc., 2300-1055 Dunsmuir St., Four Bentall Centre, PO Box 49334, Vancouver, British Columbia, Canada, V7X 1L4, MHoltby@Pretivm.com*

Abstract

The high-grade gold Brucejack Project, an underground mine located in northwestern British Columbia, Canada, is in the process of being developed. Surface topography has a dominant influence on the groundwater flow system at the mountainous, remote site, which is bounded by temperate glaciers. The complex hydrostratigraphy comprises thin, discontinuous unconsolidated deposits underlain by fractured and faulted sedimentary, metamorphic and volcanic bedrock; coupled with the subarctic climate and abundant precipitation, this geologic setting leads to considerable seasonal variation in groundwater elevations.

As part of site exploration and evaluation, five kilometres of historical underground workings were dewatered and expanded over a three year period. The resulting field observations provided a dataset not typically available at such an early stage of project development – essentially a large-scale, long-term, variable-rate pumping test.

Groundwater monitoring and numerical flow modeling were completed in support of regulatory approvals and engineering design. The numerical model was developed using MODFLOW-Surfact and was calibrated in stages to available data, including seasonal hydraulic heads, vertical hydraulic head gradients, streamflow and winter low-flow estimates, and volumetric dewatering flowrates. Two distinct approaches were used to represent the underground workings in the model; a passive approach using drain boundaries, which helped to constrain estimates of hydraulic properties, and an active approach using a fracture well. Detailed calibration to observed dewatering flowrate data and benchmarking against hydraulic head response data suggested that the bulk hydrogeological properties of this complex system were well characterized and suitable for further analyses.

The calibrated groundwater flow model was subsequently used to: 1) estimate groundwater inflow rates to the proposed underground mine throughout mining operations for the calibrated, base case scenario as well as a range of sensitivity scenarios; 2) simulate groundwater discharge rates and flow paths to possible surface water receptors under pre-disturbance conditions, throughout mining operations, at closure, and in the post-closure period; and, 3) predict drawdown throughout mining operations, recovery of the groundwater system in the closure period, and steady-state water table configuration post-closure.

Key words: Mine water hydrogeology, hydrogeological modeling, water-related mine design

Introduction

Pretium Resources Inc. is in the process of developing the Brucejack Gold Project (the "Project") at their Brucejack property located in northwestern British Columbia, Canada (Fig. 1). The Project focuses on the Valley of Kings and West Zones, which contain vein-hosted gold mineralization. Advanced exploration activities in the 1980's saw the development of approximately 5 km of underground workings. These workings were dewatered and expanded starting in 2011.

The Project will occur over an approximately 40-year period in four phases: a 2 year pre-production (construction) phase, an 18 year operations mining phase, and a 20 year closure and a post-closure phase. Mine infrastructure will include the underground mine with associated waste rock dumps, subaqueous tailings disposal, and a plant site (Fig. 2). Water-related infrastructure will include a mine water treatment plant, surface water diversion channels, and a contact water pond.

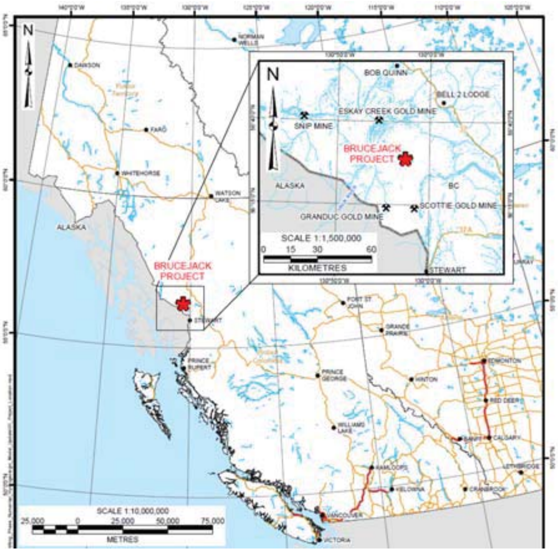

Figure 1 *Brucejack Project location map*

A three dimensional (3-D) MODFLOW-Surfact numerical groundwater flow model was developed for the Project, covering an area of approximately 12 km^2, to meet current industry standards and regulatory requirements.

This paper outlines the conceptual understanding of the hydrogeologic system, and describes the development of the groundwater flow model, with emphasis on the use of the unique dewatering dataset in model calibration and benchmarking.

The paper also describes the application of the groundwater model to support project feasibility assessment, and to predict the potential hydrogeologic impact of mining and groundwater extraction on surface water flows both during the operations period, and in the closure and post-closure periods.

Conceptual Hydrogeologic Model

Surface topography has a dominant influence on the groundwater flow system at the site. The elevation in the vicinity of the Project ranges from approximately 1,300 m to over 2,000 m at the highest peaks, while elevations in the modeled area descend as low as 500 m in the adjacent Sulphurets Creek Valley. Measured groundwater elevations suggest that the water table is a subdued replica of topography, with depths to groundwater typically greater in the uplands relative to the valley bottoms.

The climate in the immediate vicinity of the Brucejack Project is considered subarctic, with variable temperature and precipitation generally exceeding 1,900 mm/yr. Groundwater enters the flow system from infiltration of precipitation, snowmelt, and glacier melt, with a lesser component supplied by surface water infiltration in lakes. Groundwater discharge zones are pervasive in this high-topography environment, and include lakes, creeks, gullies, seeps and breaks in slope. In addition, the Brucejack Lake catchment is approximately 5.6% glaciated, and the Project is bounded by temperate glaciers.

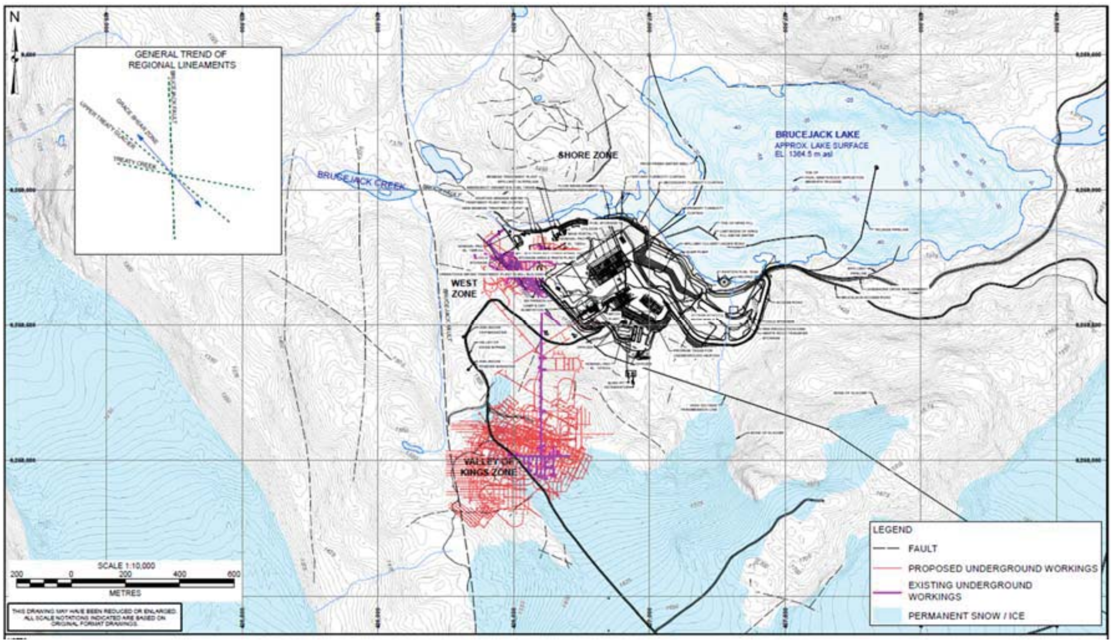

Figure 2 *Brucejack Project area site plan.*

The hydrostratigraphy at the site comprises a thin, discontinuous layer of glacial till or colluvium underlain by bedrock. Thicker unconsolidated deposits are confined to local sections of the valley bottom and are not present in the vicinity of the proposed underground mine. Regional bedrock can be broadly divided as follows:

- Triassic marine sedimentary and volcanic rocks of the Stuhini Group
- Jurassic sediments and volcanic rocks of the Hazelton Group
- Early Jurassic dikes, sills, and plugs of diorite, monzonite, syenite and granite, the most common of which are grouped as the "Sulphurets Intrusions"

Baseline characterization of the hydrogeologic system included completion of 67 point-scale hydraulic response tests in bedrock (i.e., slug tests and packer tests), and installation of a network of approximately 30 monitoring wells and vibrating wire piezometers. Site-wide, a general trend of decreasing bedrock hydraulic conductivity with depth is observed, although the point-scale hydraulic conductivity may vary by 2 to 3 orders of magnitude at any given depth. Based on available data there is no apparent relationship between hydraulic conductivity and the major structure in the immediate vicinity of the Project, the Brucejack Fault (Fig. 2). However, groundwater flow does appear to be influenced by the Bruce Fault, a westward trending feature that underlies Brucejack Creek at the outlet of Brucejack Lake (Fig. 2).

Numerical Groundwater Model Development

The conceptual hydrogeologic model was used as the basis for the development of a numerical model, built using the graphical user interface Groundwater Vistas (Environmental Simulations Inc. 2011) and the MODFLOW-Surfact code (Harbaugh et al. 2000, HydroGeoLogic 2012).

The elevation of the top grid layer was set at ground surface or glacier surface, where applicable. The model domain was divided into ten layers, ranging in thickness from 5 m in layer 1 to over 1,000 m below ridge tops in layer 10. The base of the model domain was set at sea level, which is approximately 1,000 m below the deepest extent of the proposed underground mine workings. Surface water features, including Brucejack Lake and local streams were represented by general head, drain or river boundary conditions, depending upon the conceptualization of the hydraulic connection of the feature to the groundwater system.

The numerical model was calibrated in stages to available hydrogeologic data collected within the study area, including: steady-state and transient hydraulic head targets; vertical hydraulic head gradients; streamflow data and winter low-flow estimates for the period 2008 to 2014; and, volumetric discharge data available from mine dewatering activities for the period 2011 to late-2014.

An iterative approach was adopted to adjust parameter values and compare results for the average annual, or steady-state simulations, and transient simulations for both seasonal and dewatering conditions, until a suitable calibration was achieved. The groundwater model was considered calibrated when good matches to hydraulic head targets and winter low-flow streamflows were achieved for steady-state simulations of average pre-disturbance conditions, while maintaining good matches to seasonal head variations, dewatering drawdowns and observed mine inflows for transient simulations representing seasonal water inputs and mine dewatering activities. This paper does not present the full numerical model calibration, but rather focuses on the calibration and benchmarking completed using the 2011 to 2014 mine dewatering dataset.

Numerical Analysis of Large-Scale Long-Term Pumping Test: Model Calibration & Benchmarking

Two distinct approaches were used to represent the underground workings in the model and gain insight from the available mine dewatering data: 1) a passive approach using drain boundaries, which helped to constrain estimates of hydraulic properties; and, 2) an active approach using a fracture well to simulate observed dewatering and benchmark against observed hydraulic head data.

Numerical Model Calibration

The fall 2013 to fall 2014 time period was selected for the transient calibration to observed mine inflows because it represented relatively controlled conditions with no injection of drilling water and static geometry of the underground workings. Drain boundary conditions (i.e., head-dependent boundaries) were used to represent the underground workings; the conductance of the drains was calculated using the Thiem solution and the Peaceman (1983) formula for calculating conductance for a borehole or underground opening. Elevations for water levels within the drain cells were specified according to the existing adit dimensions down to 1,300 m asl, the maximum depth at which dewatering occurred. The calibration simulation was run using 1-month stress periods, and a sufficient spin-up period to establish dynamic equilibrium.

While the calibration simulation did consider hydraulic head, vertical gradient, and streamflow targets, the primary objective was calibration to mine inflow data – observations that represented a large-scale test of the hydraulic response of the rockmass to pumping stresses. These calibration data reflected an integration of the influence of all hydraulic parameters impacting flow to the subsurface workings over an extended period of time. Furthermore, because the existing exploration workings were coincident with sections of the proposed mine workings, the observed responses and inflows are considered to be the most representative available data for predicting future conditions and behaviour.

Close agreement between simulated and observed mine inflows was achieved (Fig. 3).

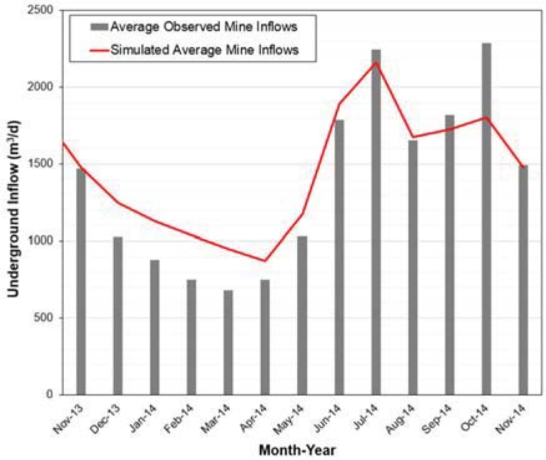

Figure 3 *Model-predicted mine inflows vs. monthly average observed mine inflows for the period November 2013 to November 2014.*

Simulated flow to the underground workings (i.e., flow to drain boundaries representing the workings) varied from approximately 900 m^3/d to 2,200 m^3/d over the fall 2013 to fall 2014 period. The lowest observed and simulated inflows occur in late-winter, before seasonal recharge associated with snowmelt commences, and the highest inflows occur during summer and early-fall. The bi-modal distribution of predicted summer and fall inflows is driven by the temporal distribution of recharge.

Numerical Model Benchmarking

Transient model benchmarking was completed for the period fall 2008 to fall 2014 to further evaluate the transient response of the model to underground dewatering. The benchmarking simulation comprised 57 individual stress periods; seasonal 6-month stress periods were used to represent the period from November 2008 to May 2010, and 1-month stress periods were used thereafter.

The Fracture Well (FWL) package available in MODFLOW-Surfact was used to simulate pumping from the underground workings. A vertical FWL was assigned within the centre of the existing underground workings, with an average radius of 2 m and a well screen from 1,390 m asl to 1,200 m asl. Due to the large radius of the adit, wellbore storage effects were incorporated. Model cells in layers 2 to 7, within which the existing workings fell, were assigned enhanced hydraulic conductivity to allow water to freely drain into the simulated well.

Average monthly pumping rates were specified using the FWL package for the period November 2011 to January 2012 and August 2012 to November 2014 (i.e., specified rates corresponded to observed pumping from the underground). An exploration drift was advanced at the site over the spring 2013 to fall 2013 period to extract a bulk sample for resources estimation purposes; the associated evolution of the underground workings was simulated in the numerical model using the MODFLOW-Surfact time-varying properties (TMP) package, which allows for the transient modification of hydraulic parameters.

A summary of the simulated and observed transient response to dewatering is provided in Table 1, and selected time series plots of simulated and observed hydraulic head responses are provided as Fig. 4. Head offsets are generally present at each calibration target location, but the groundwater time series plots illustrate that the numerical model successfully captured observed seasonal fluctuations in hydraulic head in addition to overall decline in hydraulic head in response to dewatering. This good representation was achieved despite temporal and spatial complexity introduced by irregular drilling activities, variable dewatering rates, seasonal recharge and geological uncertainty.

Table 1 *Summary of model-simulated and observed transient head response to mine dewatering.*

Well ID	Observed Responses			Simulated Responses		
	Maximum (m asl)	Minimum (m asl)	Range (m)	Maximum (m asl)	Minimum (m asl)	Range (m)
1A	1367.6	1314.7	52.9	1381.2	1328.0	53.2
1B	1369.1	1346.5	22.6	1379.2	1336.5	42.6
2A	1374.0	1361.8	12.2	1388.5	1365.3	23.1
3A	1369.4	1345.7	23.7	1368.1	1340.3	27.8
3B	1369.8	1358.4	11.4	1364.6	1347.3	17.3
4A	1383.6	1372.5	11.1	1382.4	1372.6	9.8
4B	1382.6	1364.7	17.8	1384.3	1373.2	11.1
5A	1527.0	1457.5	69.5	1517.3	1454.4	62.9
5B	1530.8	1475.7	55.1	1519.4	1454.3	65.2
6A	1378.5	1364.6	13.9	1371.2	1365.9	5.4
6B	1368.8	1363.4	5.4	1372.7	1367.4	5.3
8A	1392.2	1370.2	22.0	1387.4	1352.6	34.8
8B	1394.3	1365.4	28.9	1387.3	1352.3	35.0
9B	1487.1	1469.1	18.0	1488.2	1404.9	83.3
12A	1538.4	1485.0	53.4	1545.9	1489.9	56.0
DH19	1300.9	1358.7	57.9	1384.8	1257.6	127.2
SU77	1352.6	1464.1	111.5	1502.4	1447.1	55.3
SU82D	1475.7	1514.8	*	1525.2	1458.2	67.0
SU82S	1516.8	1534.6	*	1490.3	1442.7	47.6
SU88D	1326.6	1364.8	38.2	1363.7	1348.8	14.9

* Insufficient data (i.e., less than one year of observed heads) were available and therefore no observed range is presented.

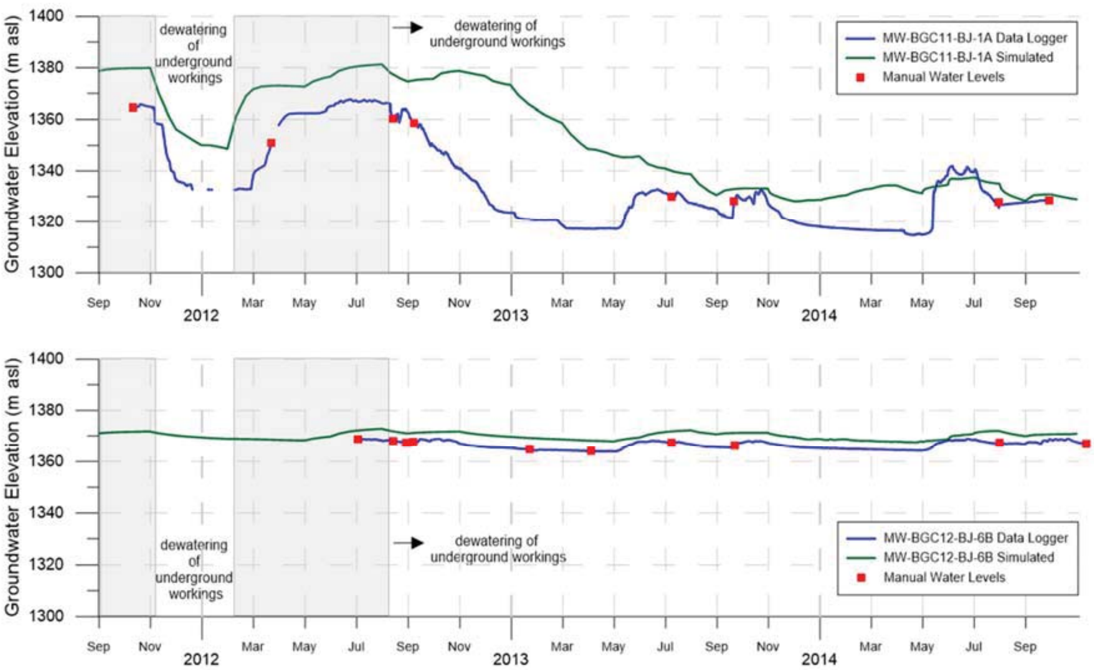

Figure 4 *Groundwater elevation time series plots showing observed and model-simulated response to underground dewatering at wells 6B and 1A.*

Numerical Groundwater Model Application

Evaluation of the results of model calibration to both pre-disturbance and post-disturbance conditions, and benchmarking to adit dewatering and transient head response suggested that the numerical representation of the hydrogeologic system was suitable for further predictive analyses.

The calibrated groundwater flow model was subsequently used to: 1) estimate groundwater inflow rates to the proposed underground mine throughout mining operations for the calibrated, base case scenario as well as a range of sensitivity scenarios; 2) simulate groundwater discharge rates and flow paths to potential surface water receptors under pre-disturbance conditions, throughout mining operations, at closure, and in the post-closure period; and, 3) predict drawdown throughout mining operations, recovery of the groundwater system in the closure period, and steady-state water table configuration post-closure.

Numerical Model Predictive Simulation Results

With the advent of mining operations, groundwater flow in the immediate vicinity of the Brucejack Project is predicted to become largely directed towards the dewatered mine workings. The average annual rate of groundwater inflow to the underground workings is predicted to remain relatively stable throughout operations, ranging between 2,500 m^3/d and 3,500 m^3/d. The overall average flow for the entire simulated mining period is 2,900 m^3/d, and model-simulated groundwater inflow to the underground workings is predicted to vary seasonally by about 2,000 m^3/d.

The elevation of the water table is predicted to be drawn down substantially throughout operations – up to approximately 400 m within the footprint of the underground workings (Fig. 5). By the end of mine life, drawdown contours are predicted to propagate over an area 2 to 3 times the size of the mine footprint, and the cone of depression associated with 10 m or more of drawdown due to mine dewatering has an areal extent of approximately 2 km by 3 km (Fig. 5).

In general, the surface water features closest to the proposed underground mine are expected to be most impacted by mine dewatering. Changes in groundwater discharge to surface water receptors was measured as a function of predicted baseflow to select monitoring points and/or gauging stations in the proximity of the Project (as groundwater baseflow was interpreted to be the sum of net groundwater flow to boundary conditions upstream of these points). A 20% reduction in average baseflow reporting to the adjacent gauging station on Brucejack Creek throughout mining operations was predicted, with some streams or reaches of streams receiving no groundwater discharge during operations.

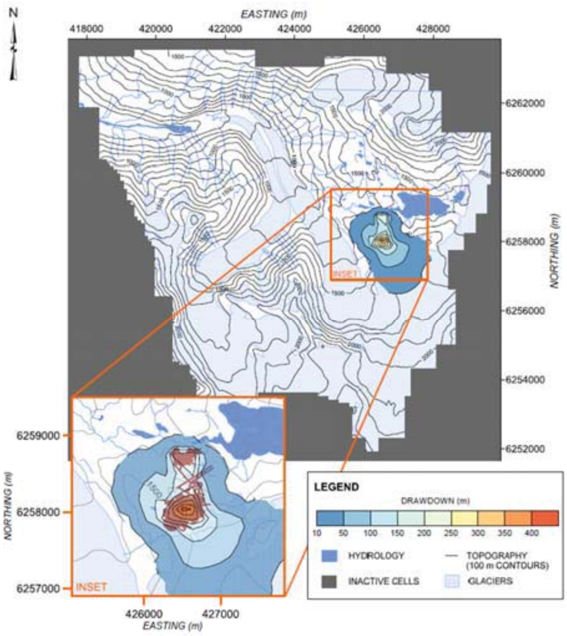

***Figure 5** Simulated drawdown at end of mine life (operations year 18).*

The transient closure and post-closure simulations indicate that most recovery happens within one year of the end of active mining operations (i.e., after dewatering ceases), with the groundwater flow system approaching a new equilibrium within 2 to 3 years after the end of active mining. Post-closure, the configuration of groundwater elevation contours is consistent with pre-disturbance conditions: the water table is predicted to be a subdued replica of the surface topography, with local groundwater flow occurring from areas of higher topographic elevation towards Brucejack Lake and Brucejack Creek. Within the footprint of the mine workings, the post-closure water table is predicted to be locally depressed compared to pre-disturbance conditions; this arises because the specified hydraulic conductivities of the mine backfill materials are higher than the surrounding bedrock. In the post-closure period, the areal extent with drawdowns of 10 m to 25 m relative to pre-disturbance conditions is approximately 0.5 km by 1 km.

Groundwater discharge to surface water receptors is predicted to return to rates approaching pre-disturbance conditions within approximately 2-3 years following the end of active mining. This finding suggests that mining operations associated with the Brucejack Project will not result in any significant long-term impact to baseflow in the Brucejack Creek watershed.

Application of Predictive Simulation Results

Results of the predictive groundwater flow model simulations were integrated with the Project site-wide water balance model (WBM), and dependent water quality prediction model used to evaluate project effects for the environmental assessment. The WBM and water quality models were also used to support water management design and evaluation, and development of triggers for monitoring and adaptive management requirements as part of project permitting.

Conclusions

A MODFLOW-Surfact groundwater flow model was developed to evaluate impacts of mine development on the groundwater flow system at the Brucejack Project, located in northwestern British Columbia, Canada. Dewatering of existing underground workings at the site afforded a unique dataset for model calibration and benchmarking – essentially a large-scale, long-term, variable rate pumping test. The numerical model was calibrated to volumetric mine inflow data and was subsequently benchmarked against the response of hydraulic heads to mine dewatering. The availability of mine dewatering data at this early stage of project development was fortuitous, as the dewatering data represent a large-scale stress to the hydrogeologic system, allowing for increased confidence in definition of hydraulic parameters and boundary conditions. Model benchmarking suggested that the bulk properties of this complex hydrogeologic system were well represented, and that the model was suitable for further analyses.

The calibrated groundwater flow model was subsequently used for a suite of predictive simulations to estimate groundwater inflow rates to the underground workings, simulate groundwater discharge rates to surface water features, and predict drawdown and recovery of the groundwater system throughout Operations and into the Post-Closure period. All results of predictive simulations were presented in support of the Project feasibility studies, environmental approvals, and regulatory permitting. The Brucejack Project received a British Columbia Environmental Assessment Certificate in March 2015, Federal Environmental Decision Statement in July 2015, and Mines Act and Environmental Management Act Permits in September 2015. The Project is currently undergoing construction.

Acknowledgements

The authors thank Pretium Resources Inc. for involving them in the Brucejack Project.

References

Environmental Simulations Inc. (2011) Groundwater Vistas – Version 6. Documentation available online at http://www.groundwatermodels.com/Groundwater_Vistas.php

Harbaugh AW, Banta ER, Hill MC & McDonald MG (2000) Modflow 2000. The U.S. Geological Survey Modular Ground-water Model – User Guide to the Modularization Concepts and Ground-water Flow Process. U.S. Geological Survey Open File Report 00-92, 130 pp.

HydroGeoLogic Inc. (2012). Modflow-Surfact – A Code for Analyzing Subsurface Systems. Documentation available online at http://www.hglsoftware.com/Modflow.cfm

Peaceman DW (1983) Interpretation of well-block pressure in numerical reservoir simulation with nonsquare grid blocks and anisotropic permeability. *Society of Petroleum Engineers Journal*, 23(3): 531-543.