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Memo

To: Jason Rempel

Date: March 4, 2009

Re: Update of MODFLOW Model of Davidson Project

Executive Summary

This document details an updated groundwater model for the Davidson EA. Key differences between this version of the model and the previous version are a change in the model domain to allow groundwater to flow to Glacier Gulch and Simpson Creek watersheds from the mine area; revision of the mine grid so that the adits and mine could be treated as simple drains without internal inactive zones; an extensive sensitivity analysis of the key parameters; and more thorough transient simulations of 700 Adit development, mine operations and post-closure.

The model predicts that typical groundwater discharge rates to the adits and mine during pre-development and operations will be in the range of 20 L/s to 40 L/s. This modeled discharge rate is unchanged by the inclusion of the Glacier Gulch fault, by the inclusion of hypothetical fault zones in the Kathlyn Glacier area, or by changes in the hydraulic conductivity of the Hazelton and Skeena formations. The predicted discharge rate, however, is affected by the hydraulic conductivity of the immediate mine-area rocks (e.g., granodiorite), by the subglacial recharge rate, and the effectiveness of the 700 Adit grout.

The integrity of the grout in the 700 Adit is an operational parameter that can be field-adjusted. The other two parameters, the granodiorite hydraulic conductivity and the subglacial recharge rate, can be used to determine an upper bound range of groundwater discharge rates to the adits and mine; this upper bound range is 30 L/s to 60 L/s. The model predicts that a plant-site water storage capacity of 1000 m^3 could handle the upper bound groundwater flow predictions. It would be prudent to increase the backup storage volume above this value for system down-times and to accommodate excess surface runoff.

The model predicts that the mine will reduce the water table in its immediate vicinity. As a result, the groundwater discharge component (i.e., baseflow) to four of the creeks is predicted to decline. The greatest reduction in baseflow is predicted for Glacier Gulch Creek, at which 5 percent to 18 percent baseflow reductions are predicted. Kathlyn Creek Tributary A3 is expected to experience declines in groundwater baseflow of 3 percent to 12 percent. Kathlyn Creek Tributary A and Kathlyn Creek (main branch) may experience drops in baseflow of up to 3%. All other streams will not experience noticeable reductions in flow.

As a result of the overall water table depression of the mine, groundwater that has contacted the mine is not likely to impact any of the downgradient users during mine operations.

Post-mining, when the 1066 Adit and 700 Adit are sealed, groundwater discharge to area creeks will increase to approximately pre-1960 levels.

When groundwater has reached a post-mining steady state, the model predicts that groundwater from the mine area will ultimately discharge at Club Creek, Glacier Gulch Creek and Kathlyn Creek. Depending on the hydraulic conductivity and integrity of the glacial till underlying Lake Kathlyn, some groundwater flow from the mine may discharge at Lake Kathlyn.

Transport simulations of the post-closure mine show that the transport of solutes in the mine will occur slowly. Because the mine is near the top of the mountain, the groundwater is predicted to flow downward from the mine to deeper bedrock strata before discharging to creeks. Post-closure, groundwater quality may change in downgradient wells, as the source(s) of groundwater change(s). Groundwater geochemistry is expected, for the most part, return to that which was present in the area prior to the drilling of the 1066 Adit.

In order to detect and monitor post-closure water quality impacts from the mine, a monitoring program is recommended, including six new monitoring wells and a comprehensive seep survey. It is recommended that two wells (or well screens) be developed in the new monitoring locations, a shallow well in the upper weathered bedrock and a deeper well in a significant fracture zone in competent bedrock.

Introduction

After submission of the Davidson Project EA, I was contracted by Rescan to review the groundwater work in order to assist with responding to government and public questions, because the original modeler was no longer available. In reviewing the work, I identified some important areas where the model could be improved. These were presented to Blue Pearl in October 2008, and I began making these modifications to the model at that time. Subsequently, I was provided with comments from government regulators and the public. Most of these comments were similar to what I had identified in my original review. The purpose of this report is to outline improvements that have been made to the groundwater model, and to respond to some of the comments and questions from the regulators and the public.

Methodology

General Comments

This document presents the results of three-dimensional groundwater flow modeling for the Davidson Project. The model was designed to predict groundwater discharge to the underground mine and evaluate potential impacts of mining on the groundwater flow regime and associated surface water discharge processes.

The modeling was done using Visual MODFLOW version 4.3. I used the finite-difference code MODFLOW rather than a finite-element code such as FEFLOW, which can simulate discrete fractures, because MODFLOW is a decades-old, thoroughly tested and reliable program that is appropriate for the model objectives. MODFLOW has the further advantage of being popular, meaning the number of people available to review and critique a MODFLOW model is larger. So in the interests of transparency, MODFLOW was selected as the numerical code for the Davidson model.

One issue that often arises when MODFLOW is used in fractured bedrock setting concerns the applicability of a continuum model for such an environment. A comprehensive review of all the literature on this issue is beyond the scope of this document. However, it is my opinion that, outside of specific research-grade field sites with many gigabytes of data on fracture location and interconnectedness, a discrete fracture model cannot be justified. I would like to direct the reader to the many relevant studies in which continuum models were successfully applied to fractured bedrock settings (including, for example, Tiedeman and Hsieh, 2001; Gleeson and Manning, 2008). It should be noted that in some of these studies (for instance, Tiedeman and Hsieh, 2001), the use of continuum models did not preclude the treatment of heterogeneity.

Table 1. Modeling Approach

Main Step	Sub-Steps
1. Mine treated as higher-K zone based on location of previous drillholes. (Granodiorite incorporated into Hazelton.)	a. Steady-State Calibration to heads and flow, with free-draining 1066 Adit b. Transient Simulation of 700 Adit (455 days) c. Transient simulation of Mine Operations (10 years) d. Sensitivity analysis of drain conductance e. Sensitivity analysis of Glacier Gulch Fault
2. Granodiorite (including mine) treated as higher-K zone	a. Steady-State Calibration to heads and flow, with free-draining 1066 Adit b. Transient Simulation of 700 Adit (455 days) c. Transient simulation of Mine Operations (10 years) d. Sensitivity to faults in mine vicinity
3. Sensitivity Analysis on key parameters	a. Steady-State Calibration to heads and flow, with free-draining 1066 Adit b. Transient Simulation of 700 Adit (455 days) c. Transient simulation of Mine Operations (10 years).
4. Mine Flooding	a. 30 year transient, to determine rate of rebound in flows b. Transient transport simulation using MT3D version 5.2
5. Post-Closure Contaminant Migration	a. Steady-State simulation of post-closure pathlines from mine b. Evaluation of endpoints c. Sensitivity to Glacial Till hydraulic conductivity d. Transport simulation using MT3D

The Davidson model was accomplished in several steps. These steps are listed in Table 1. The general progression of the simulations is shown in the right column of Table 1. First, an initial steady state condition was simulated in which the existing 1066 Adit was allowed to drain freely. The steady state runs was followed by up to three transient runs, one during the development of the 700 Adit, one during mining, and an optional third simulation of the first thirty years after closure. Initially, the period of the 700 Adit drilling and mining were treated as discrete steady state runs. However, the transient analyses showed that steady state conditions were not achieved during the life of the mine, and the predicted groundwater discharge to the mine at steady state were significantly lower than that predicted using transient simulations. For this reason, transient simulations were conducted.

The left hand column of Table 1 shows the evolution of the model over time. In the First Calibration, although the granodiorite was not treated as a separate unit, the area within the proposed mine impacted by previous drilling was assigned a higher hydraulic conductivity than the unmined areas of the Hazelton formation. Within the First Calibration, a sensitivity analysis was completed on the drain conductance of the 700 Adit to evaluate the impact of grouting the tunnel on predicted in flows. A second sensitivity analysis was completed in which the hydraulic conductivity of the Glacier Gulch Fault zone was increased to be a multiple of the Skeena (Bowser) formation hydraulic conductivity.

In the Second Calibration, the estimated extent of the granodiorite zone was modeled as a separate unit with a higher hydraulic conductivity than the volcanic Hazelton materials. The reason for the change in the treatment of the granodiorite is due to our experience that granodiorite can be more fractured and permeable than volcanics such as andesite. As part of the Second Calibration, a sensitivity analysis was completed to determine the effect of a transmissive fracture zone in the mine area that could provide a conduit for enhanced flow of subglacial recharge into the mine.

After the two calibration phases, during which the parameters were adjusted in a manner such that the calibration targets were met, a sensitivity analysis was completed. In the sensitivity analysis, the parameters were adjusted to either their reasonable limit for the system or until the model did not meet the calibration targets. For example, a reasonable limit for a parameter such as the bulk hydraulic conductivity of the bedrock could be the value at which the water table is so flat that the simulated 1066 Adit is currently dry.

The objectives of the last two phases of modeling were to evaluate the rate of rebound in the water table following mining and to determine of likely trajectories of mine-impacted groundwater. For modeling step 4, the effect of mine development on groundwater discharge to nearby creeks was examined. Then, transient, post-mining simulations were completed to evaluate the rebound in groundwater discharge to mine vicinity creeks after mining is complete and the 700 and 1066 Adits are sealed.

Finally, in modeling step 5, an analysis of the potential water quality impacts post-closure was assessed through transport simulations in which the post-closure mine area rocks were treated as a constant source of a generic compound with an initial composition of 100%.

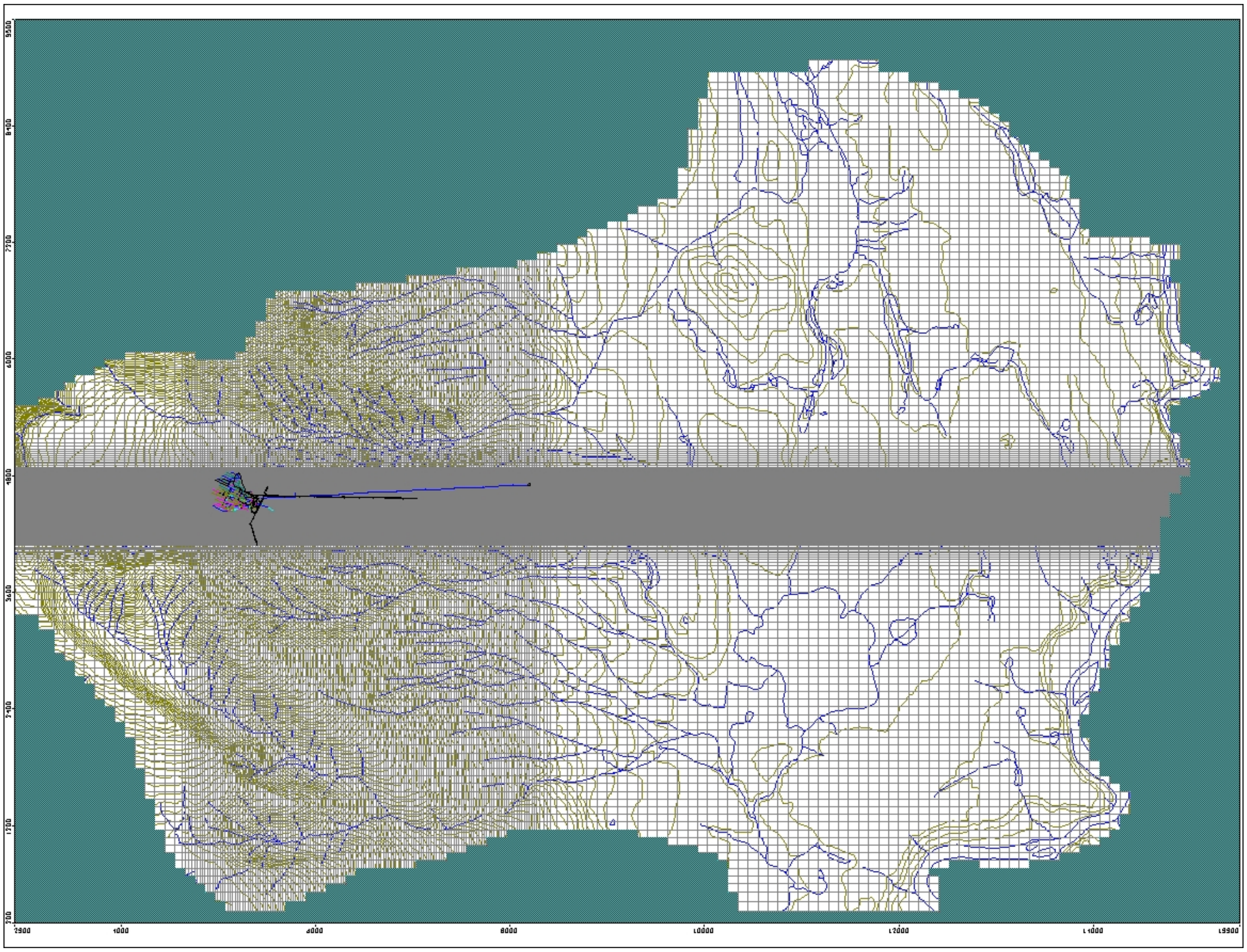
Model Domain

The groundwater flow modeling was conducted using Visual MODFLOW, version 4.3, a commercial finite difference code sold by Schlumberger Water Services. The model was developed as a three-dimensional model extending from Hudson Bay Mountain to the Bulkley River, as shown in Figure 1.

The grid for the three-dimensional runs was composed of 221 rows, 118 columns and 17 layers. The grid is shown in Figure 2.

Figure 1. Model Domain

Figure 2. Model Grid

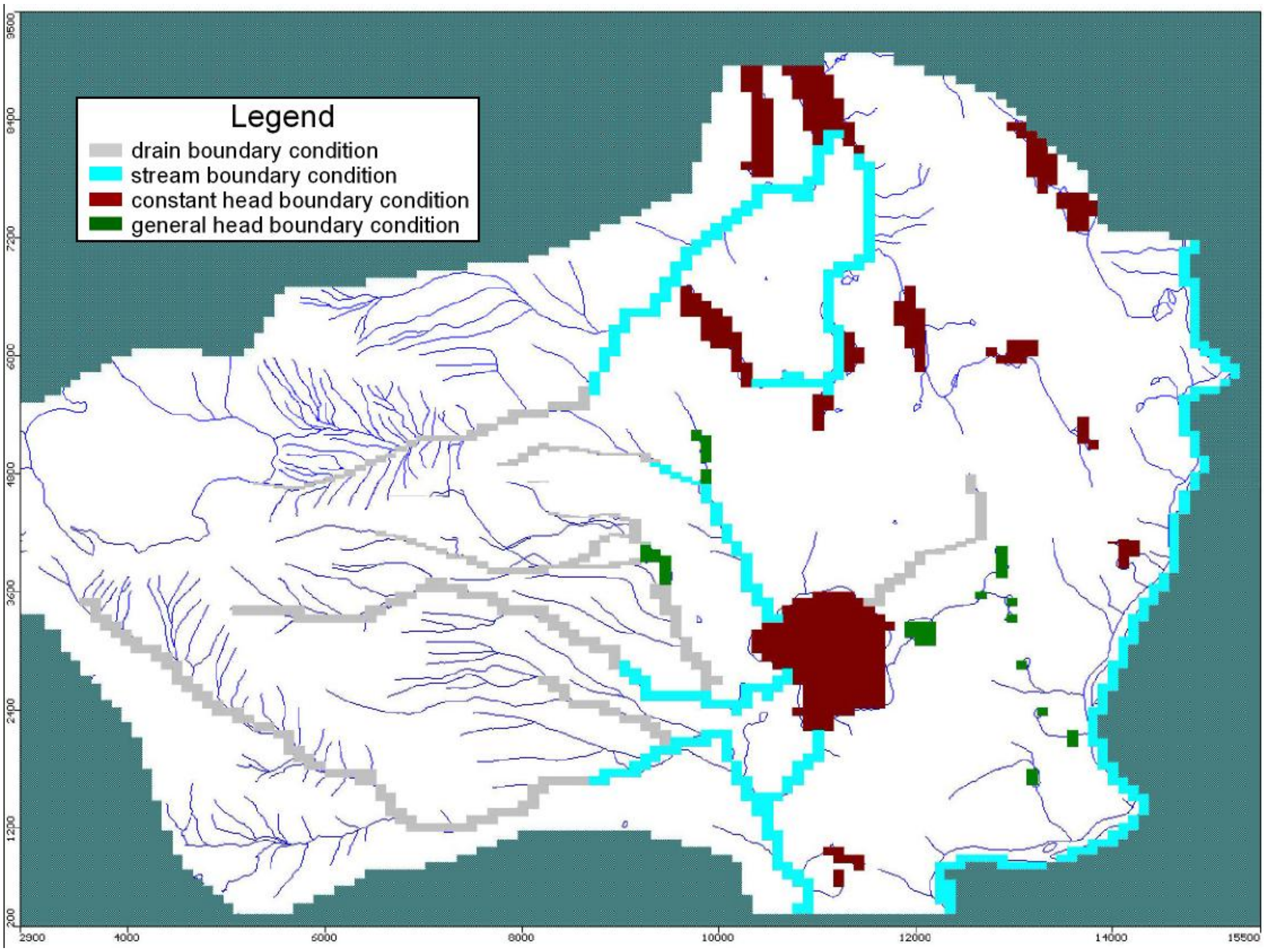


Boundary Conditions

Layer 1 boundary conditions are shown in Figure 3. The eastern boundary is the Bulkley River, treated as a stream in the model, with an assumed bed width of 120 m, a streambed thickness of 1 m, and a bed hydraulic conductivity of $1x10^{-4}$ m/s. For purposes of the model, the Bulkley River stage was assigned a constant value of 440 masl.

The stream type boundary condition was used for the lower portions of Glacier Gulch Creek, Kathlyn Creek, Club Creek and Simpson Creek, as well as the outflow from Lake Kathlyn. For these smaller streams, the streambed had a thickness of 1 m, and a hydraulic conductivity of $1x10^{-6}$ m/s. The modeled width of the streams ranged from 1 m to 3 m.

Figure 3. Layer 1 Boundary Conditions



Fourteen constant head zones were defined to correspond to lakes. The most important lake was Lake Kathlyn, which was assigned a hydraulic head of 500 masl. Marshy areas were assigned general head boundary conditions. For all of the general head conditions, the bed thickness was assumed to be 1 m and the hydraulic conductivity assumed to be $1x10^{-6}$ m/s.

In the upper reaches of the creeks, drain boundaries were assigned, with conductance calculated using a conductance per unit area of 0.1 m/d.

Drains were also used for the 1066 and 700 Adits. The drains were placed in Rows 80 to 103 of the model, following the trajectory of the adits. A composite section showing the drains is shown in Figure 4. In the transient simulations of the 700 Adit development, the adit was divided into five segments that corresponded to the tunnel configuration at the end of five three-month periods (i.e., 3 months, 6 months, 9 months, 12 months and 15 months after start of boring). The drains in each of these segments were "turned on" three months prior to the completion of the segments. In other words, the entire length that would be completed at the end of the first three months was activated within the model at Time=0. At Time=3 months, the entire design length of the adit after 6 months was treated as a drain for groundwater.

The adit drains were assigned a conductance of 5 m^2/day in the First Calibration runs and lowered to 0.5 m^2/day in subsequent runs, to simulate the proposed grouting. A further discussion of drain conductance can be found below.

Drains were also used to simulate the dewatered mine. Like the 1066 Adit, these drains were assigned a conductance of 5 m^2/day. These drains were placed in Rows 66 to 122. Some of these drains can be seen in Figure 4. Note that the all of the mine drains are not shown in Figure 4, only the ones that are found in the same rows as the adit drains. A plan view of all the mine drains is shown in Figure 5.

Four recharge zones were defined, as shown in Figure 6. However, as indicated in the figure, only two unique values of recharge were applied in the model. Under the Kathlyn Glacier, recharge entered the system at a rate of 150 mm/y to 250 mm/y, depending on the calibrated hydraulic conductivities. Elsewhere recharge to groundwater was a constant value of 150 mm/y.

Figure 4. Composite Section Showing Adits, Rows 80 to 103 (2X Vertical Exaggeration)

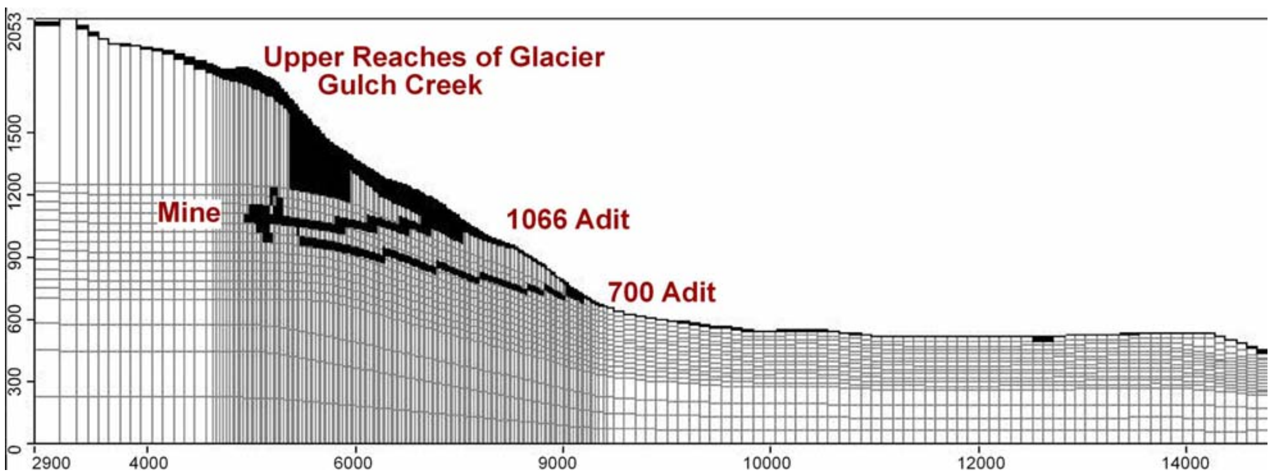


Figure 5. Location of Model Mine Drains

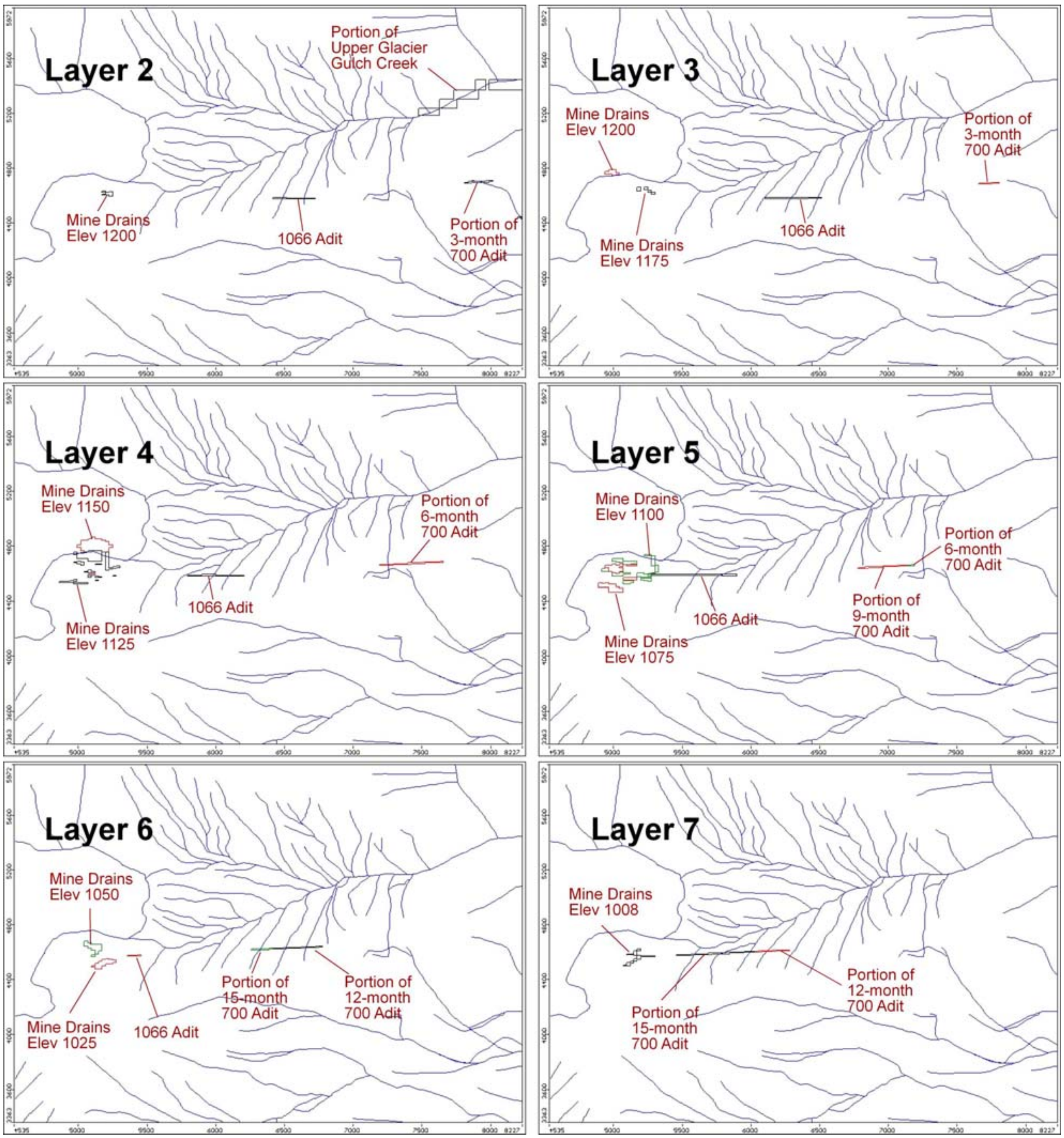
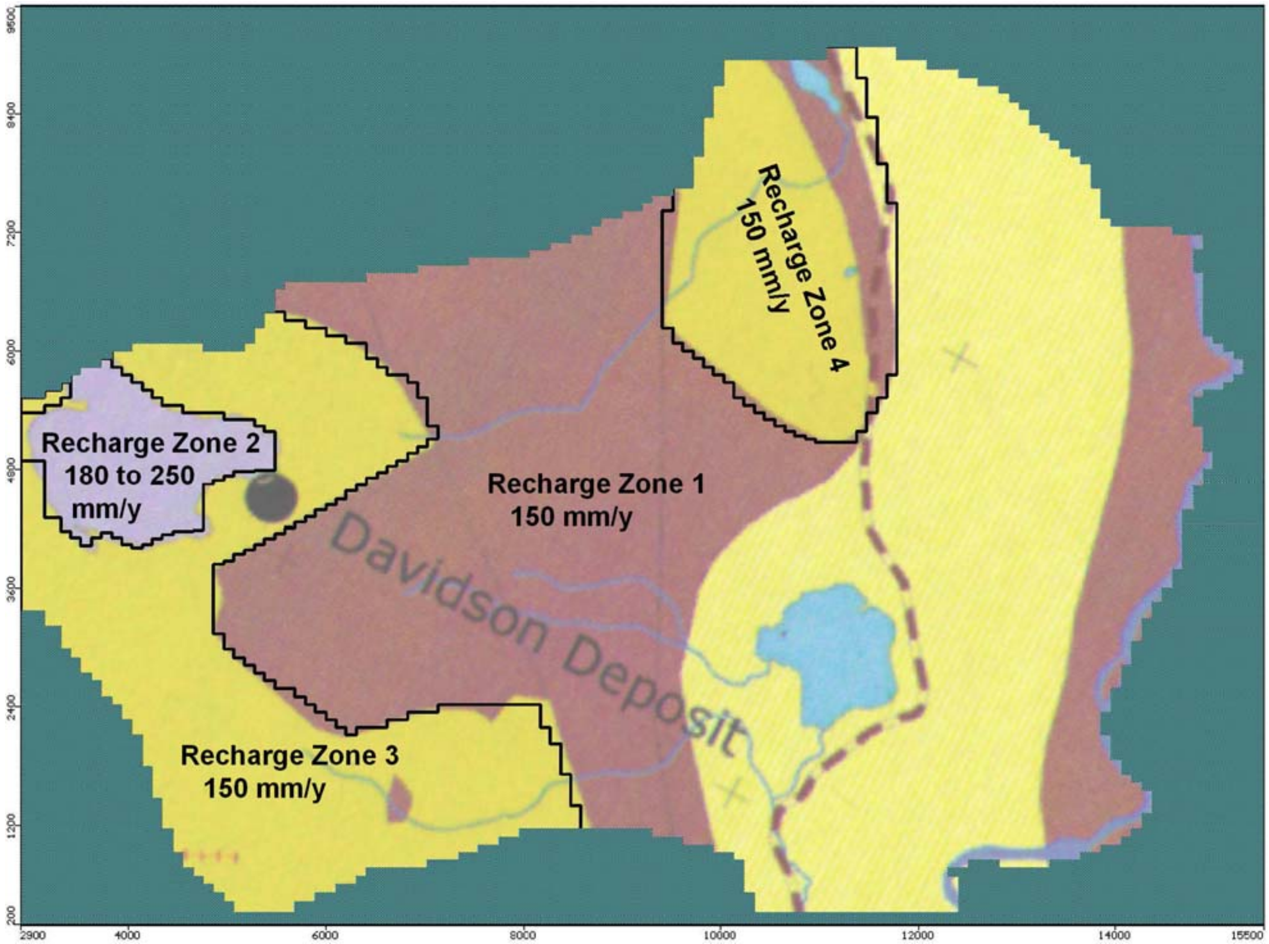


Figure 6. Recharge Zones



Note: The background to Figure 6 is a portion of the geology map presented as Figure 3.3-2 of the EA Application.

Flow Properties

Hydraulic property zones were defined roughly by stratigraphic unit. Representative layers are shown in Figures 7 to 12. A section showing model layers is presented in Figure 13. The hydraulic properties are listed in Table 2.

Table 2. Hydraulic Properties

Material	Hydraulic Conductivity (m/s)		Specific Storage (1/m)	Specific Yield	Total Porosity
	Horizontal	Vertical			
Hazelton Volcanics (White)	$1x10^{-8}$ to $6x10^{-8}$	isotropic	$5x10^{-6}$	0.01	0.02
Skeena Rocks (Dark Blue)	$1x10^{-7}$ to $2x10^{-7}$				
Layer 1 Fractured Bedrock, < 40 m thick (Light Gray)	$3x10^{-6}$				
Layer 1 Fractured Bedrock, 40-200 m thick (Royal Blue)	$5x10^{-7}$	isotropic	$5x10^{-6}$	0.02	0.05
Mine Area Rocks (Dark Gray)	$2x10^{-7}$ to $5x10^{-7}$				
Skeena Rocks at Bulkley River (Purple)	$3x10^{-6}$ to $1x10^{-5}$				
Hudson Bay Mountain Stock (Olive)	$1x10^{-8}$	isotropic	$5x10^{-6}$	0.002	0.005
Glacier Gulch Fault Zone (Maroon)	$1x10^{-7}$ to $2x10^{-5}$	$2x10^{-7}$	$5x10^{-6}$	0.01	0.02
Layer 1 Glacial Till (Green)	$1x10^{-7}$ to$1x10^{-5}$	$1x10^{-6}$	$9x10^{-4}$	0.1	0.25
Layer 2-6 Glacial Deposits (Teal)	$1x10^{-5}$ to $2x10^{-5}$	$1x10^{-6}$	$2x10^{-5}$	0.2	0.3

Figure 7. Hydraulic Conductivity Zones, Layer 1

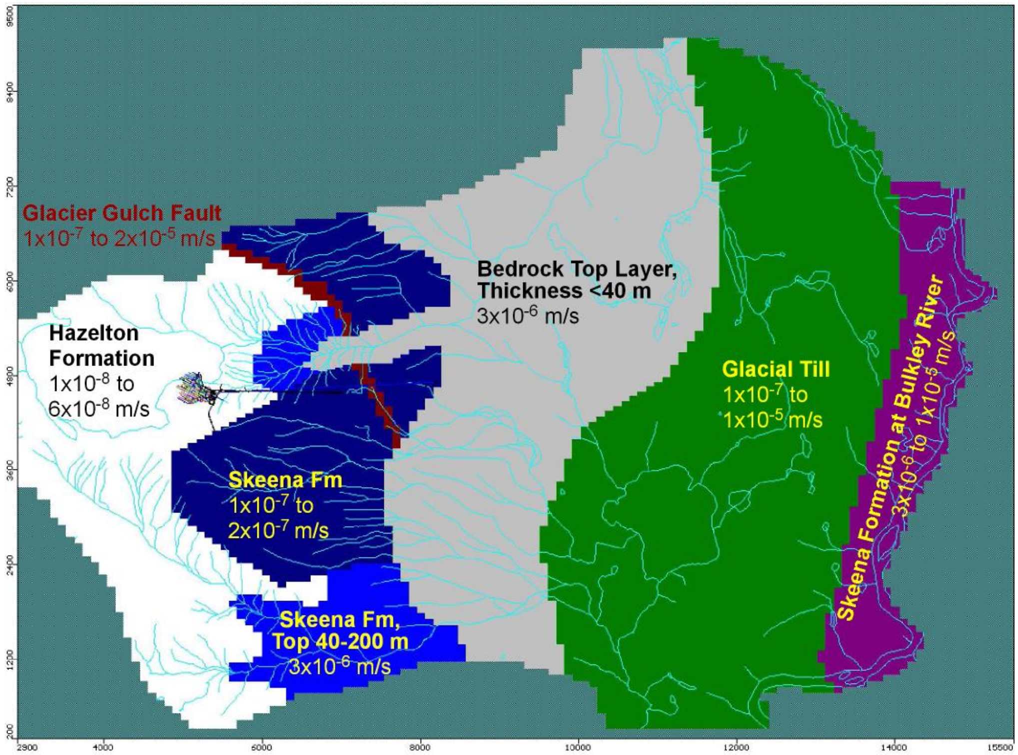


Figure 8. Hydraulic Conductivity Zones, Layer 2

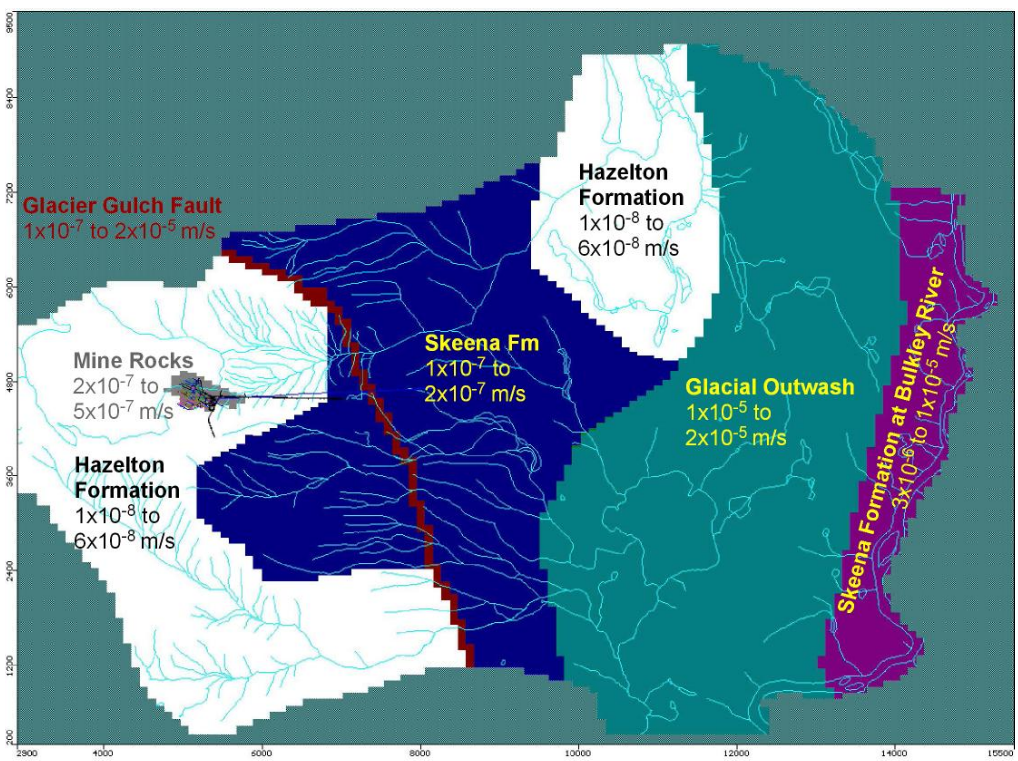


Figure 9. Hydraulic Conductivity Zones, Layer 5

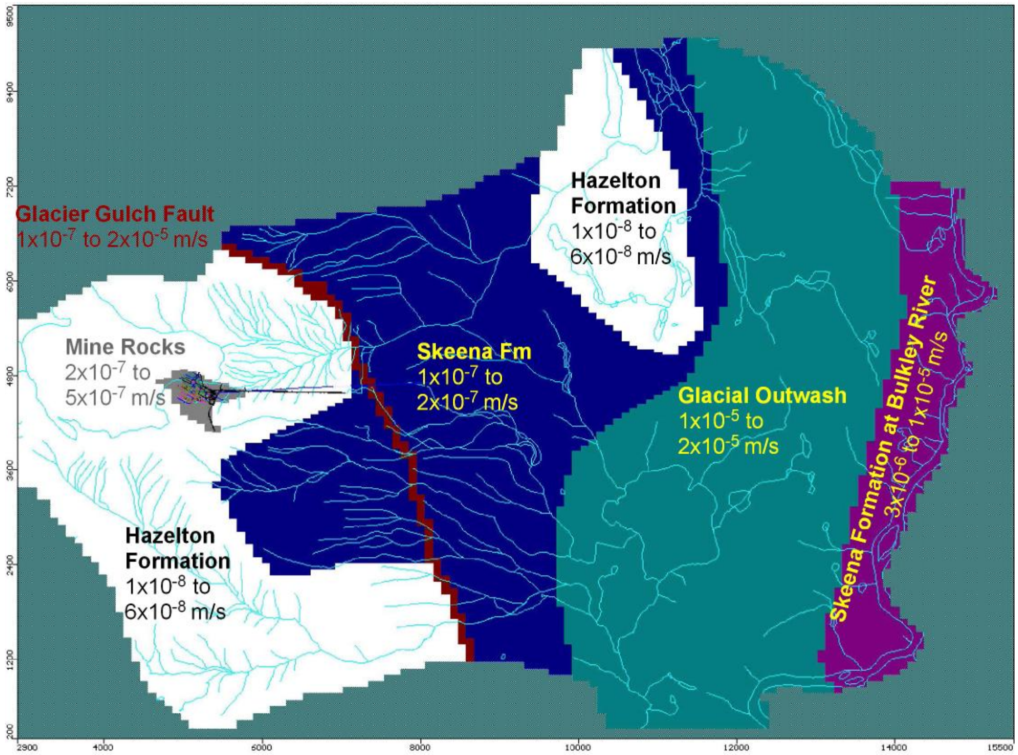


Figure 10. Hydraulic Conductivity Zones, Layer 13

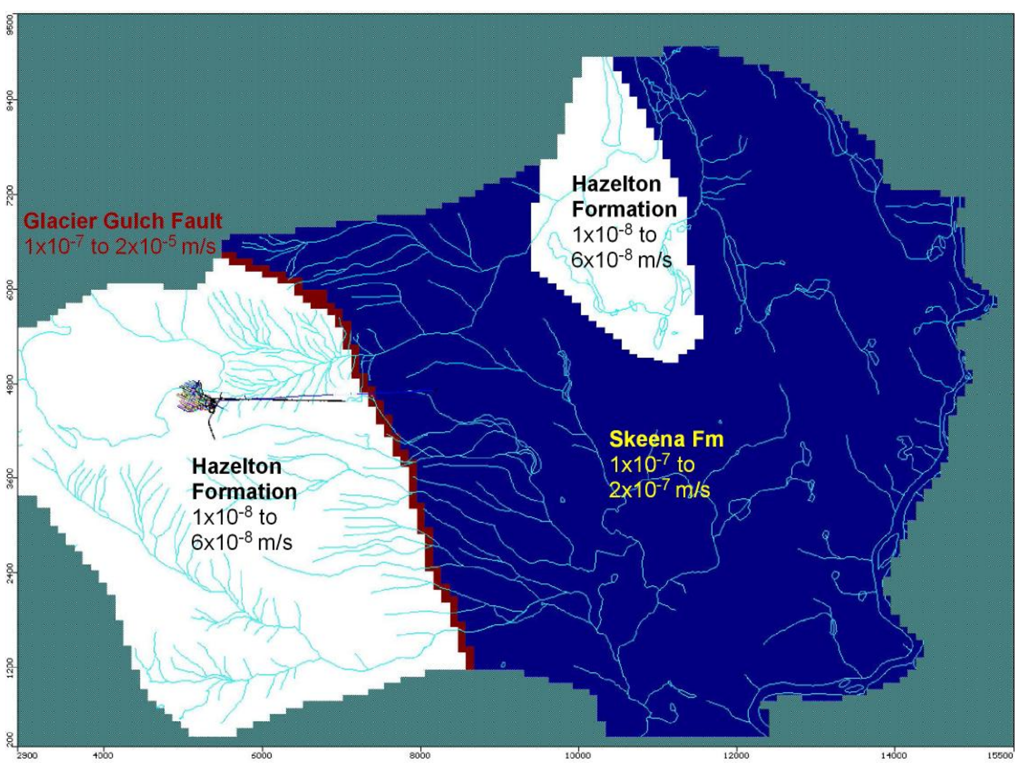


Figure 11. Hydraulic Conductivity Zones, Layer 14

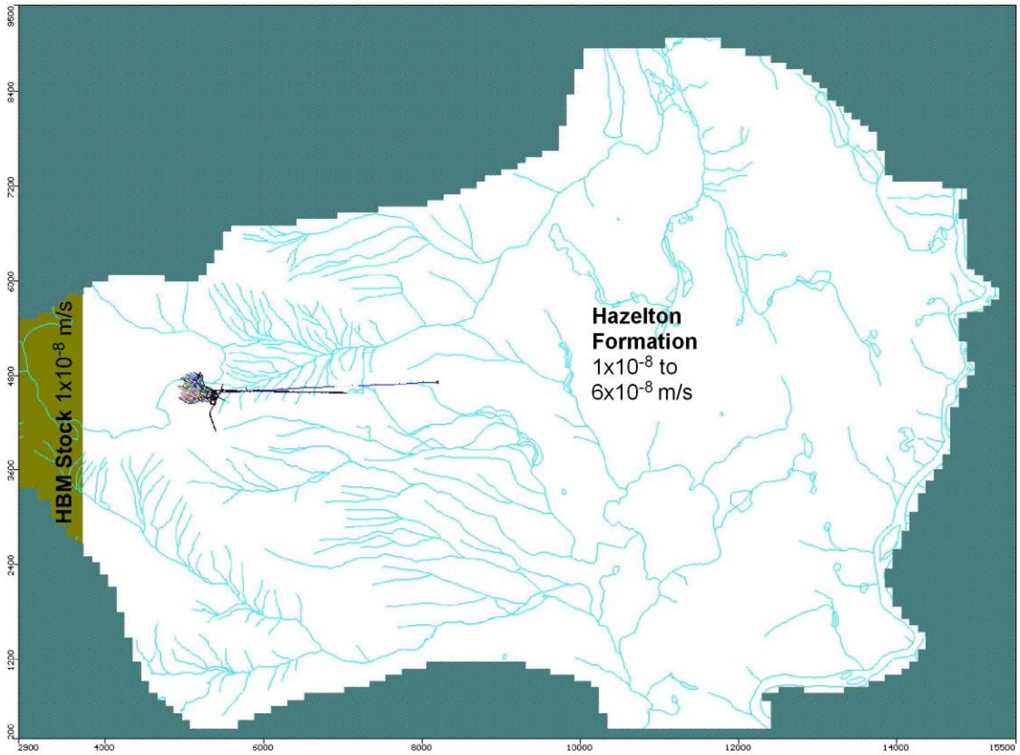


Figure 12. Hydraulic Conductivity Zones, Layer 17

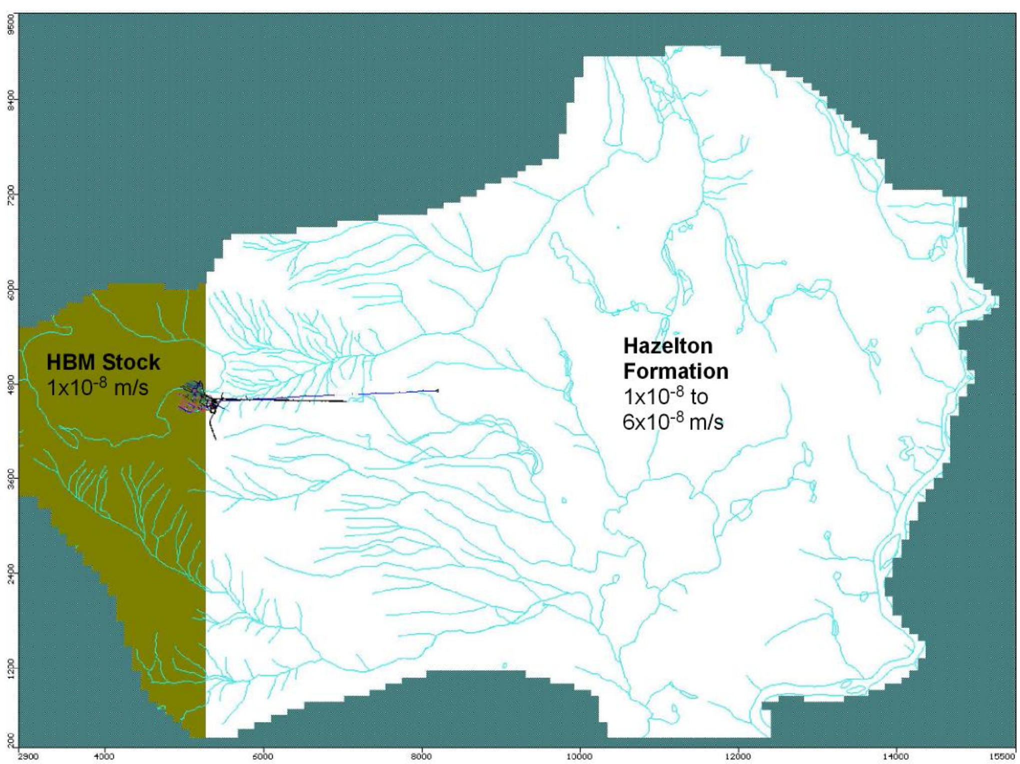
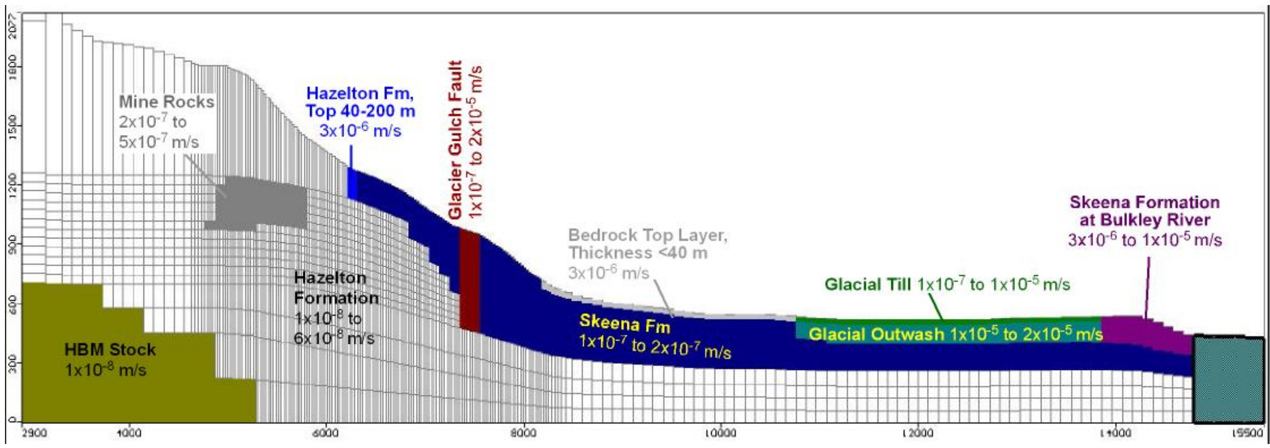


Figure 13. Hydraulic Conductivity Zones, Row 102 (2X Vertical Exaggeration)



<u>*Solver, Rewetting Parameters and Initial Conditions*</u>

The MODFLOW 2000 pre-conditioned conjugate gradient (PCG2) solver was used for all simulations. A maximum head change convergence criterion of 0.05 m and a maximum residual convergence criterion of 10 m^3/d were used. Because of the steepness of the slope and the unconfined (i.e., nonlinear) nature of the flow processes in the surficial layers, a damping factor for the PGC2 was set to 0.5. All other PCG2 parameters were kept at their default values.

The bottom eight layers of the model were kept saturated throughout the simulations. The bottom of the mine was located in Layer 7. The top nine layers of the model were treated as confined/unconfined layers, with the possibility of becoming dry if the head computed for a cell was below the bottom of the cell. If a cell becomes dry at any time during the solution of a model, it is taken out of the MODFLOW solution. In an area of steep topography, cells can be inadvertently computed to be unsaturated during the solution process. For this reason, the rewetting option for MODFLOW was used. For all runs, a dry cell was re-introduced into the model if the head in the cell beneath the dry cell was 10 m above the bottom of the dry cell. The head assigned the rewetted cell was computed from the active cells surrounding it. In general, rewetting calculations were conducted every eight iterations for steady state models and transient simulations in which the water table was being drawn down during mining, and every two iterations for post-mining transient models. In all simulations, a maximum of 500 outer iterations and 25 inner iterations were allowed.

Because the process of rewetting dry cells can significantly increase the simulation time of a model, due to an increase the time required for model convergence, the initial condition for the initial steady state runs were selected to be equal to the midpoint elevation of the Layer 1 cells. In this manner, the initial condition for the initial steady state runs had no dry cells.

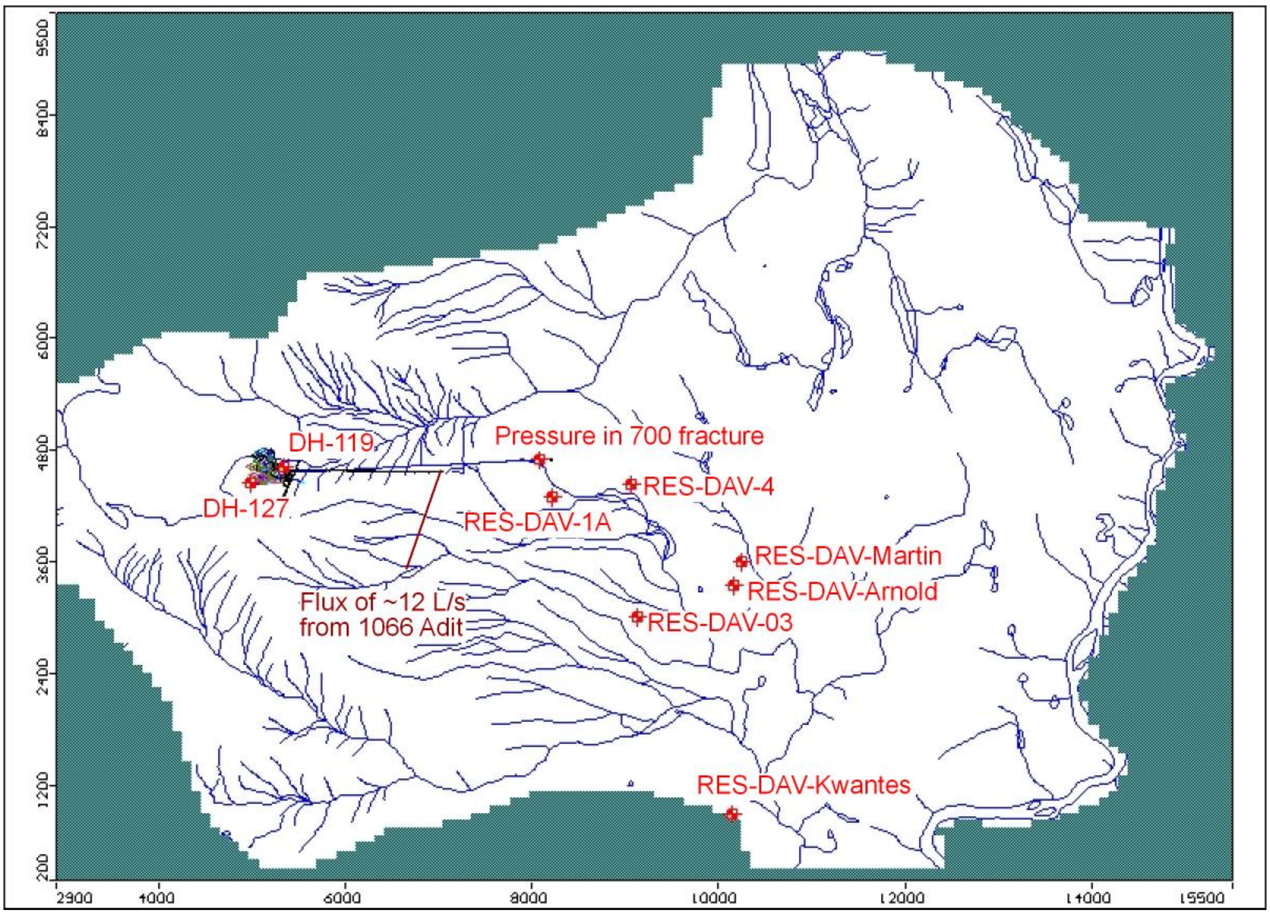
For certain parameter combinations during the sensitivity analysis, some of the convergence criteria were relaxed. In the steady state runs, either the rewetting interval during the initial steady state was raised to 16 iterations or the convergence criterion was raised to up to 0.6 m.

For transient dewatering analyses, the rewetting interval was sometimes raised from every 8 iterations to up to every 11 iterations. The runs in which the convergence criteria were relaxed are noted below in the text.

Calibration Targets

Figure 14 shows the calibration targets for the model. In total, the model was calibrated to head measurements in eight wells, one fracture zone encountered in the 700 drillhole, and long-term steady flows from the 1066 Adit.

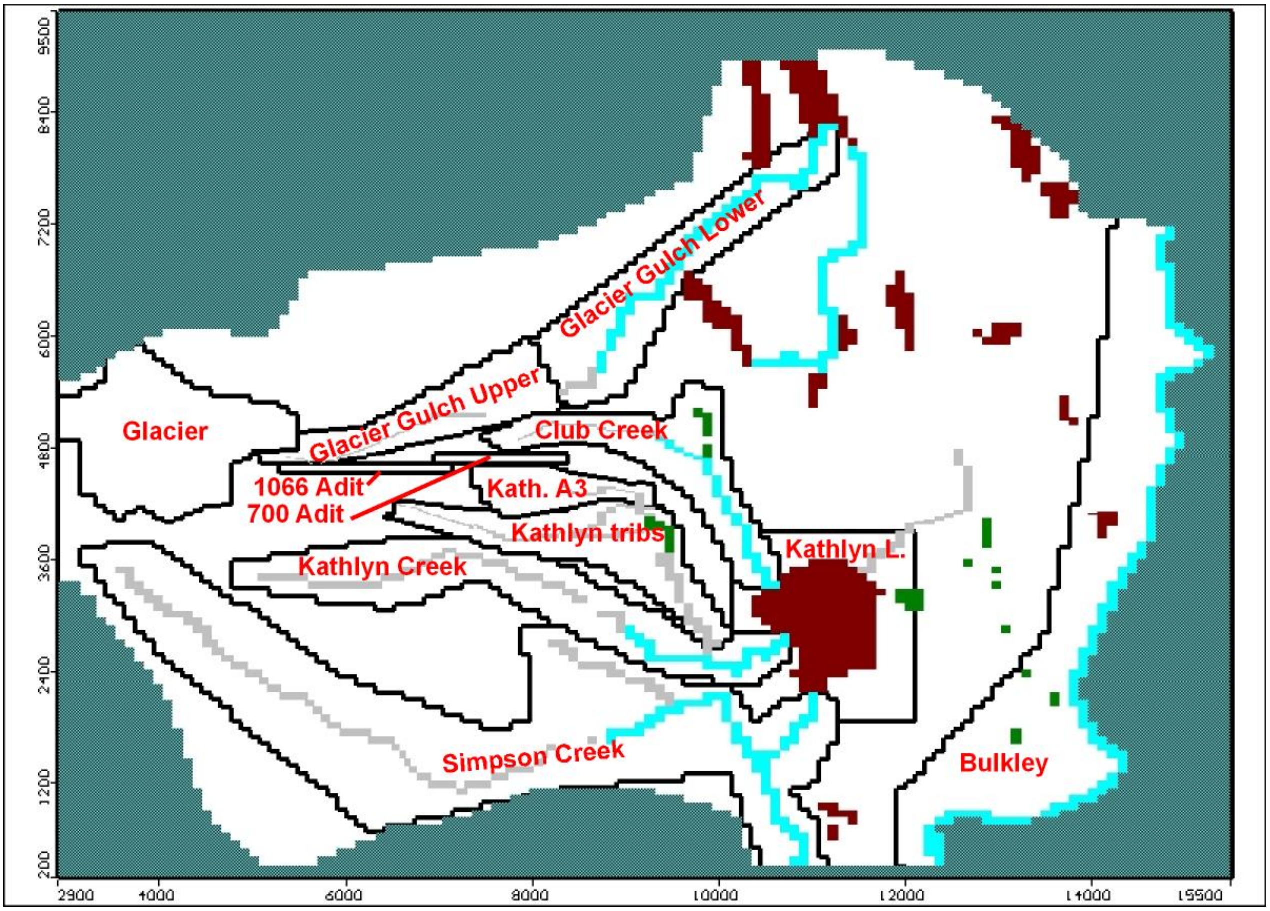
Figure 14. Calibration Targets for Initial Steady State Model



Zonebudget

In order to quantify the groundwater-surface water interaction, groundwater fluxes to the boundary cells shown in Figure 3 were examined. For ease of analysis, a number of zones were defined so the fluxes could be integrated within Visual MODFLOW. Figure 15 shows the locations of the zones in Layer 1. Groundwater discharge and recharge from the significant nearby surface water bodies was calculated. In addition, flows out of the 1066 Adit, 700 Adit and the Mine drains were calculated. The zones that encompassed these mine features extend to lower layers, and are not completely evident in Figure 15. The zones related to mine features were designed to encompass the drains shown in Figure 5.

Figure 15. Zones Used in Flux Calculations



First Calibration – Initial Simulations Without Glacier Gulch Fault

Calibration to Current Conditions

In the initial First Calibration runs, no consideration was made for enhanced permeability at the Glacier Gulch Fault. For this calibration, the model results were compared with head measurements at monitoring wells and the measured pressure in a fault zone at the 700 Adit pilot hole. The results were further calibrated to the average flow of approximately 12 L/s observed at the 1066 Adit.

Two First Calibration runs were selected for the predictive modeling. The input parameters for these two runs are shown in Table 3. In Calib 1A, the Hazelton volanics were assigned a hydraulic conductivity of $3x10^{-8}$ m/s. By contrast, the Hazelton formation hydraulic conductivity in Calib 1B was twice that value, at $6x10^{-8}$ m/s. In order that the model would have similar calibration statistics for the monitoring wells on the mountain, the Skeena formation hydraulic conductivity was reduced in Calib 1B relative to Calib 1A. In other words, raising the hydraulic conductivity of one required the lowering of the hydraulic conductivity of the other to meet the calibration targets.

In both Calib 1A and Calib 1B, the recharge rate under the Kathlyn Glacier was set to 180 mm/y.

Table 3. Best-Fit Hydraulic Conductivity Values (m/s), First Calibration

Material	Hydraulic Conductivity Values (m/s)			
	Calib 1A		Calib 1B	
	Horizontal	Vertical	Horizontal	Vertical
Hazelton Volcanics	$3x10^{-8}$	isotropic	$6x10^{-8}$	isotropic
Skeena Rocks	$2x10^{-7}$	isotropic	$1x10^{-7}$	isotropic
Mine Area Rocks	$5x10^{-7}$	isotropic	$2x10^{-7}$	isotropic
Skeena Rocks at Bulkley River	$3x10^{-6}$	isotropic	$1x10^{-5}$	isotropic
Layer 1 Glacial Till	$1x10^{-5}$	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Layer 2-6 Glacial Deposits	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-5}$	$1x10^{-6}$
Calibration Statistics for All Wells				
Normalized Root Mean Squared Error (NRMSE)	6.0%		5.6%	
Residual Mean (m)	1.4		7.5	
Calibration Statistics for Site Wells Only (DAV-1A, DAV-03, DAV-04, 700 Adit Pressure)				
NRMSE	11.0%		7.1%	
Residual Mean (m)	-9.4		-3.8	
Predicted Outflow at 1066 Adit (L/s)	16		11	

Once the Hazelton and Skeena hydraulic conductivities were selected, the model was calibrated to the hydraulic conductivity of the mine area rocks. This parameter was adjusted until the 1066 adit outflow was matched. In Calib 1A, the mine area hydraulic conductivity was a factor of 17 higher than the surrounding Hazelton rocks. For Calib 1B, with a higher Hazelton formation hydraulic conductivity, the mine hydraulic conductivity was a factor of 3 greater.

The head calibration results are shown in Figures 16 and 17. For both models, the normalized root mean square error is less than 10%, indicating that, compared to the range of data available, the error in the model is acceptable.

The head contours in Layer 3 of the model are shown in Figures 18 and 19. Layer 3 was selected because it is rather shallow, intersects 1066 Adit, and has fewer dry cells than Layers 1 and 2. It can be seen that the greatest difference in the predicted heads between Calib 1A and Calib 1B occurs upgradient of the mine, under the Kathlyn Glacier. There are no monitoring wells in this area with which to differentiate the two calibration runs.

Figure 16. Calibration Statistics, Calib 1A

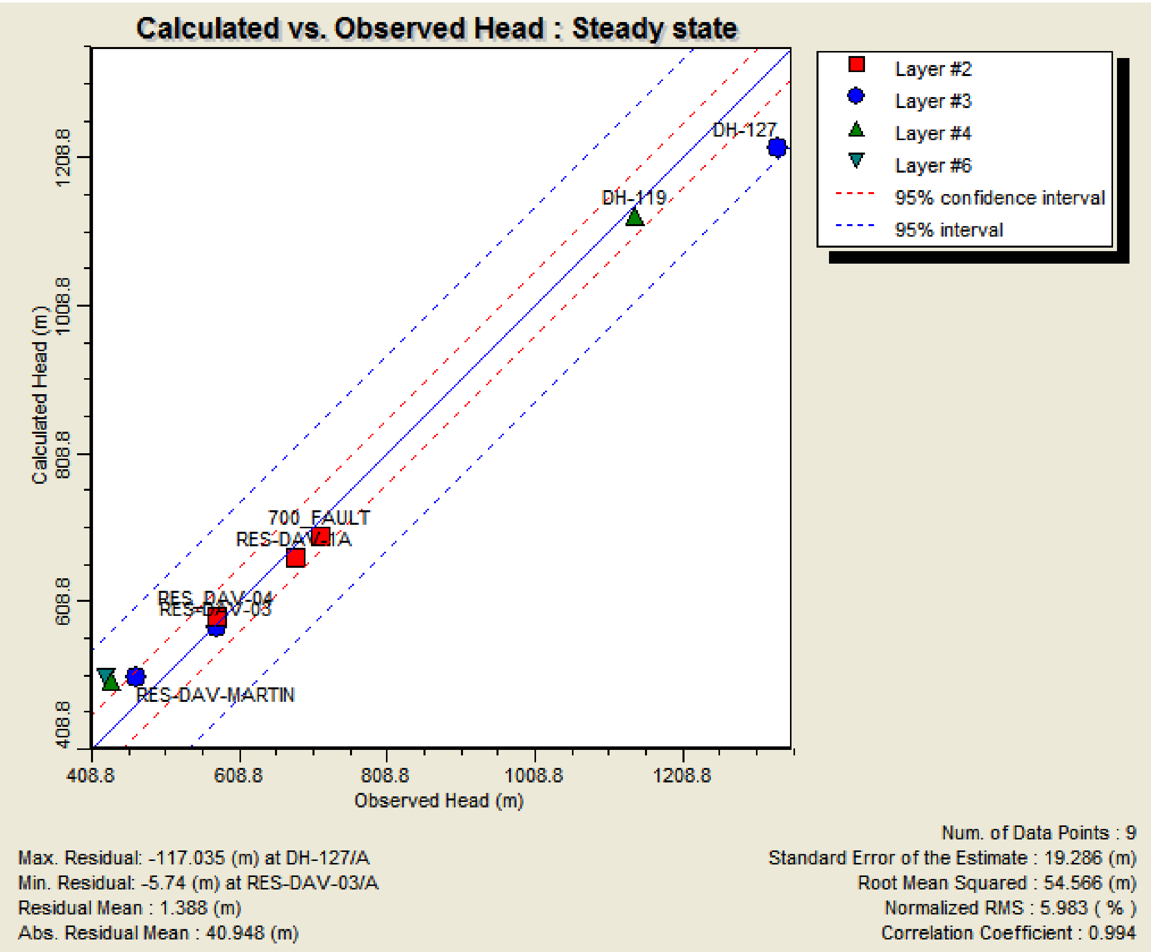


Figure 17. Calibration Statistics, Calib 1B

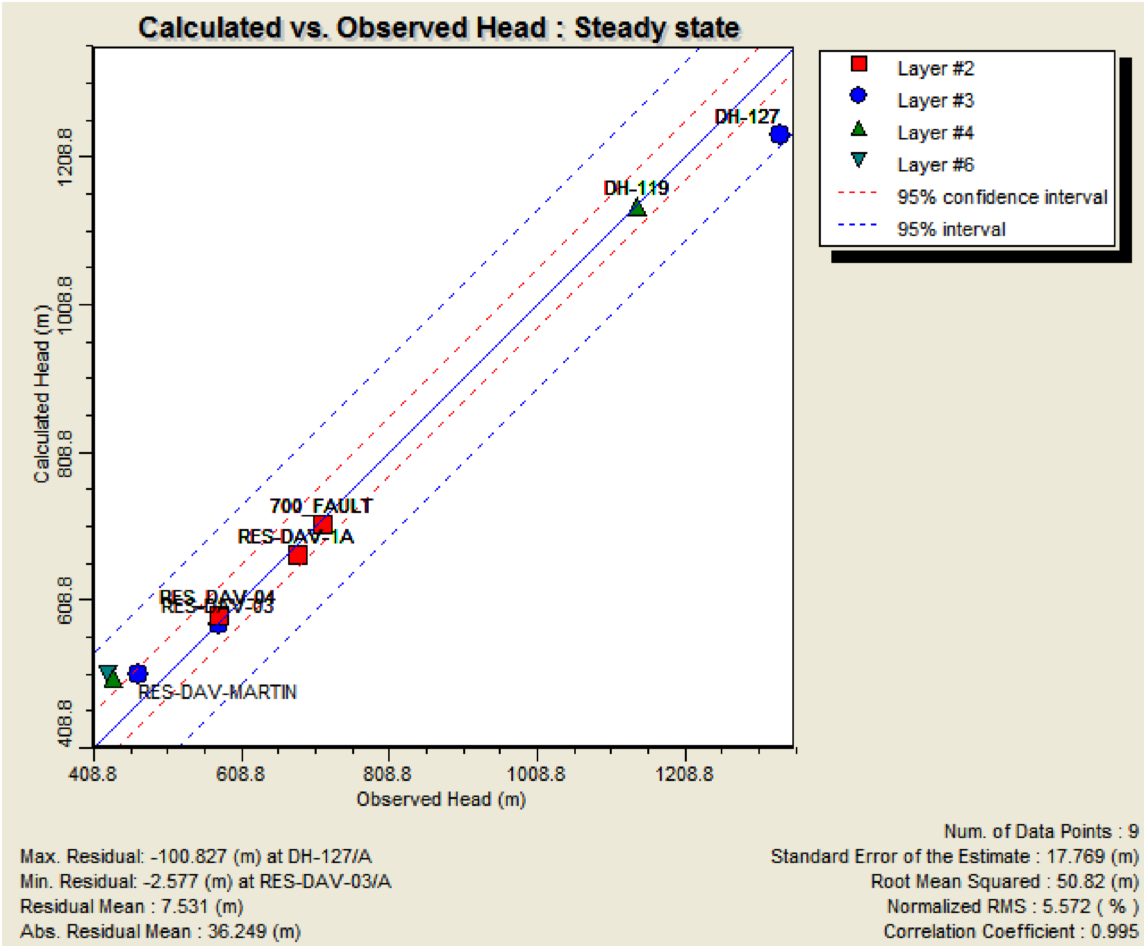


Figure 18. Predicted Heads in Layer 3, Calib1A

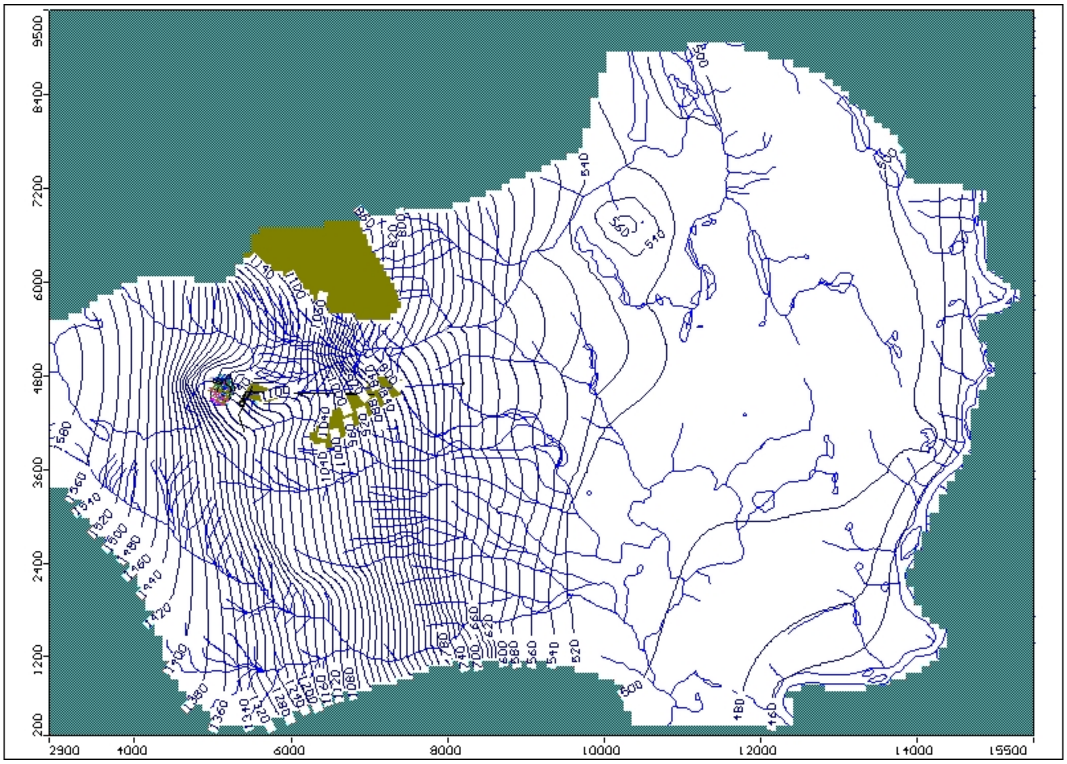
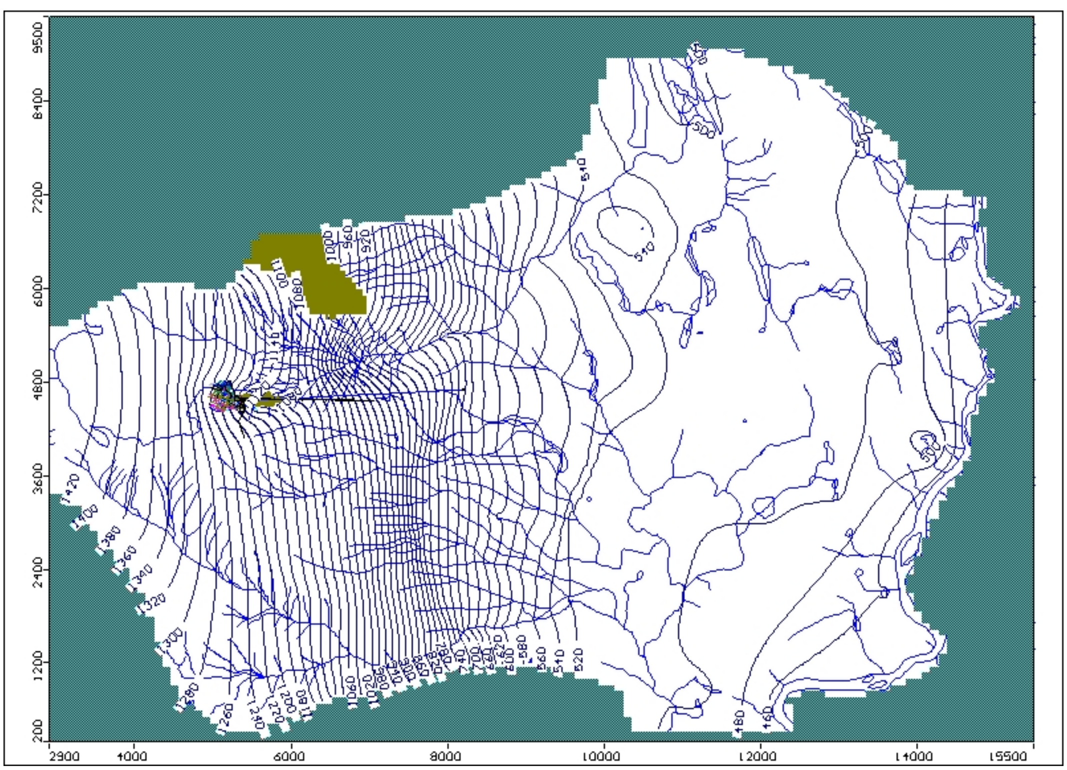


Figure 19. Predicted Heads in Layer 3, Calib1B

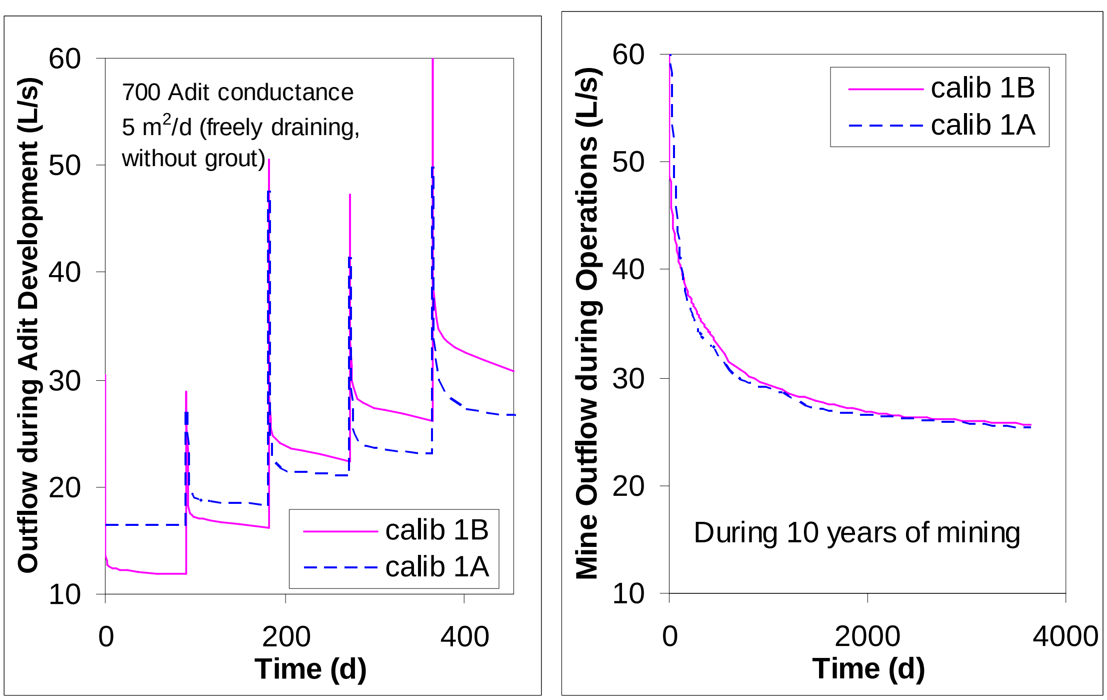


Transient Simulations of 700 Adit Development and Mining

In the transient simulations of the development of the 700 Adit, a series of drains was activated to indicate progression of adit boring. These adit sections were "turned on" in the model in three-month intervals. In other words, at Time=0, the model drains corresponding to entire section of the adit to be completed at the end of three months were activated. Then at Time=91 days, the model drains corresponding to the entire section of the adit to be completed at the end of six months were also turned on. By Time=364 days, the entire adit was treated as a drain in the model.

The predicted groundwater discharge to the adits, in the absence of grout, is shown in the left-hand graph of Figure 20. In these simulations, groundwater was allowed to freely enter the adits but not return to the groundwater. It can be seen that at the start of every three-month period, there is a spike in groundwater discharge to the adit. As expected, the peak discharge occurs immediately after the point at which the entire adit becomes active as a drain. In the model, the groundwater discharge is calculated at a time of 1.4 hours after all the drains are activated. At this time, the predicted maximum groundwater outflows are 50 L/s and 61 L/s for Calib 1A and 1B, respectively. Recall that these are the fluxes predicted for a *freely draining* adit, without the proposed grout. Estimated groundwater discharge rates when the grout is introduced are presented in the next section.

Figure 20. Predicted Mine Flows, Calib 1A and 1B



The right-hand graph in Figure 20 shows the predicted mine outflow assuming the entire mine is drained starting on day 1 of mining. For this reason, the extreme early time outflows are higher than 60 L/s. In reality, dewatering of the entire mine will not begin on Day 1 of mining.

Furthermore, the mine will be progressively backfilled, so that the entire volume will not function as a drain. The model predicts that, even under this extreme assumption, groundwater discharge to the mine by Day 5 of mining would be 55 L/s and 48 L/s for the two options and drop over time to 23 L/s and 24 L/s for Calib 1A and 1B, respectively.

Sensitivity to Drain Conductance

Because the 700 Adit will be grouted to minimize groundwater flow into the adit, a series of runs was completed to evaluate the impact of grouting on adit outflows. The results for Calib 1B, the parameter set that predicted the higher groundwater discharge to the mine, are shown in Figure 21. For the case of freely flowing groundwater, or for a model drain conductance greater than 5 m^2/d, the peak groundwater discharge rate is 61 L/s. If the grout creates a zone which presents resistance of 5 times that of the rock, or approximately an effective hydraulic conductivity of $2x10^{-8}$ m/s, the peak groundwater discharge would drop to 46 L/s. A further drop to an effective hydraulic conductivity of $2x10^{-9}$ m/s (drain conductance of 0.1 m^2/d) would reduce the predicted peak groundwater discharge during adit development to 20 L/s. A well-functioning grout should be able to provide a lower effective hydraulic conductivity than even the lowest conductance shown in Figure 21. However, in the interest of conservatism, a drain conductance of 0.5 m^2/d (a grout hydraulic conductivity of approximately $1x10^{-8}$ m/s) is used in the rest of the models presented in this document.

Figure 21. Predicted Fluxes, Calib 1B, With Varying 700 Adit Drain Conductance (in m^2/d)

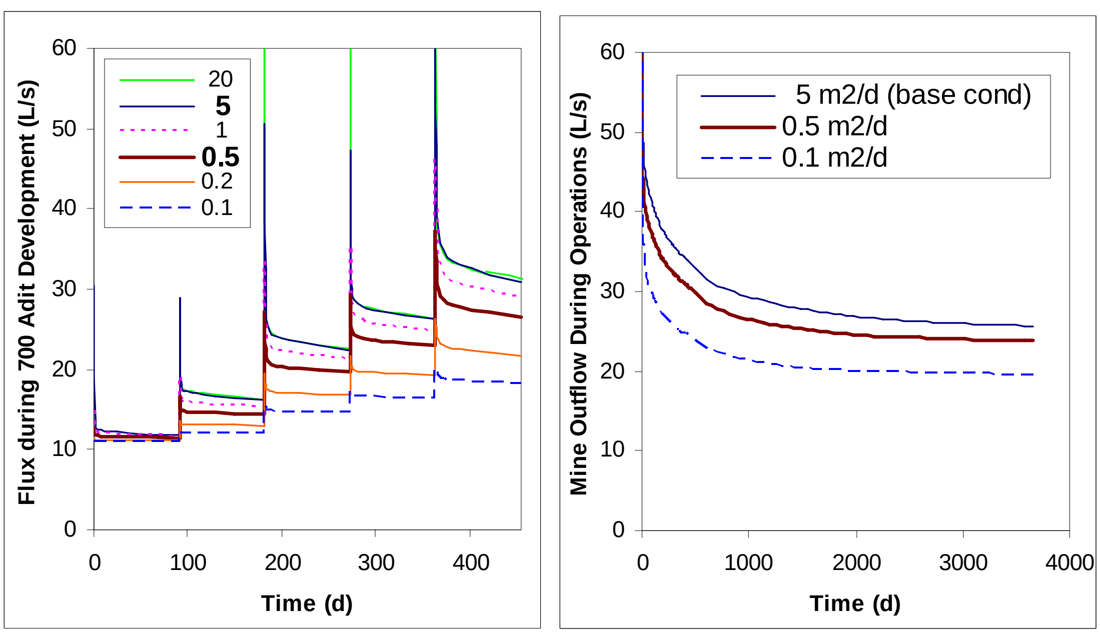


Table 4 shows the predicted adit and mine fluxes for Calib 1A and 1B when the drain conductance is lowered from 5 m^2/d to 0.5 m^2/d in order to simulate the influence of the proposed grout on groundwater discharge to the adits.

Table 4. Predicted Adit and Mine Flows (L/s) Using Drain Conductance of 0.5 m^2/d for 700 Adit

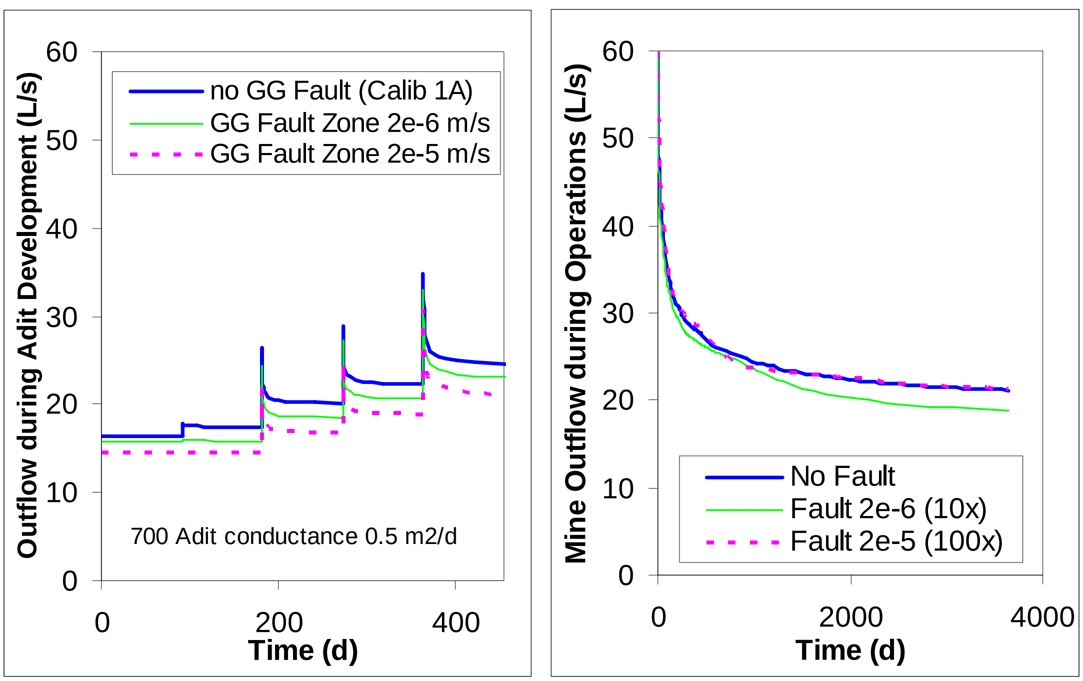
Discharge Zone	Calib 1A	Calib 1B
Peak Modeled 700 Adit Flow[1]	35	29
Mine Flow 5-d into Mine Operation[2]	51	43
End of Mine Life Flow	21	22

Note: [1]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[2]Mining Simulation assumes entire mine becomes a groundwater drain on Day 1 of mining

Sensitivity to Glacier Gulch Fault

The Glacier Gulch Fault zone was modeled as an area of enhanced permeability, with a specified hydraulic conductivity that is a multiple of the Skeena Formation's hydraulic conductivity. As shown in Figures 7 through 13, the Glacier Gulch Fault zone was treated as a 200-metre wide zone, with the width of the zone selected to equal the size of the grid cells at the southern boundary of the model.

Figure 22. Predicted Mine Fluxes with Inclusion of Glacier Gulch Fault



The results of the simulation (shown in Figure 22) indicate that, because of its orientation relative to the mine and to Hudson Bay Mountain (i.e., curving around the mountain midway up the slope), it does not play a large role in the rate of groundwater discharge to the mine. Keeping all other parameters equal while raising the hydraulic conductivity of the Glacier Gulch fault zone *lowers* the groundwater discharge to the mine by lowering the overall water table within the mountain.

In the Second Calibration, the Glacier Gulch fault was not included in the model.

Second Calibration – With Granodiorite

Introduction

As indicated in the First Calibration results, the hydraulic conductivity of the bulk bedrock units needed to be low to create the shallow, steep water table observed at the site. Simulation of the observed groundwater discharge to the 1066 Adit required the treatment of the mine as a higher-hydraulic conductivity zone within the mountain. The rationale for the increase in hydraulic conductivity in the mine area was that there could be ungrouted drillholes in this area.

However, there could be another explanation for the apparent higher hydraulic conductivity in the center of the mountain. That is the presence of a different rock type, granodiorite, which can be more permeable than, for instance, a volcanic andesite. To explore the possibility that the mine-area granodiorite could play an important hydrogeologic role, a second set of calibrations was completed in which the dimension of the granodiorite, to the best of our current knowledge, was included in the model. The hydraulic conductivity distributions with the granodiorite for Layers 2 and 5 and Row 102 are shown in Figures 23 and 24. Layers 1 and 13 through 17 are unchanged from previously.

For these runs, the hydraulic conductivity of the Layer 1 glacial till unit was assigned an isotropic hydraulic conductivity of 1×10^{-6} m/s (see Post-Closure Modeling section for rationale). The underlying glacial outwash deposits were assigned a horizontal hydraulic conductivity of 2×10^{-5} m/s and a vertical hydraulic conductivity of 1×10^{-6} m/s. The Skeena formation at the Bulkley River was assigned an isotropic hydraulic conductivity of 1×10^{-5} m/s.

The sub-glacial recharge rate was also raised in these simulations from 180 mm/y to 250 mm/y. A further sensitivity analysis on the recharge rate is presented in the Sensitivity Analysis section below.

Figure 23. Second Calibration Hydraulic Conductivity Zones, Layer 2 and Layer 5, with Granodiorite as Separate Unit

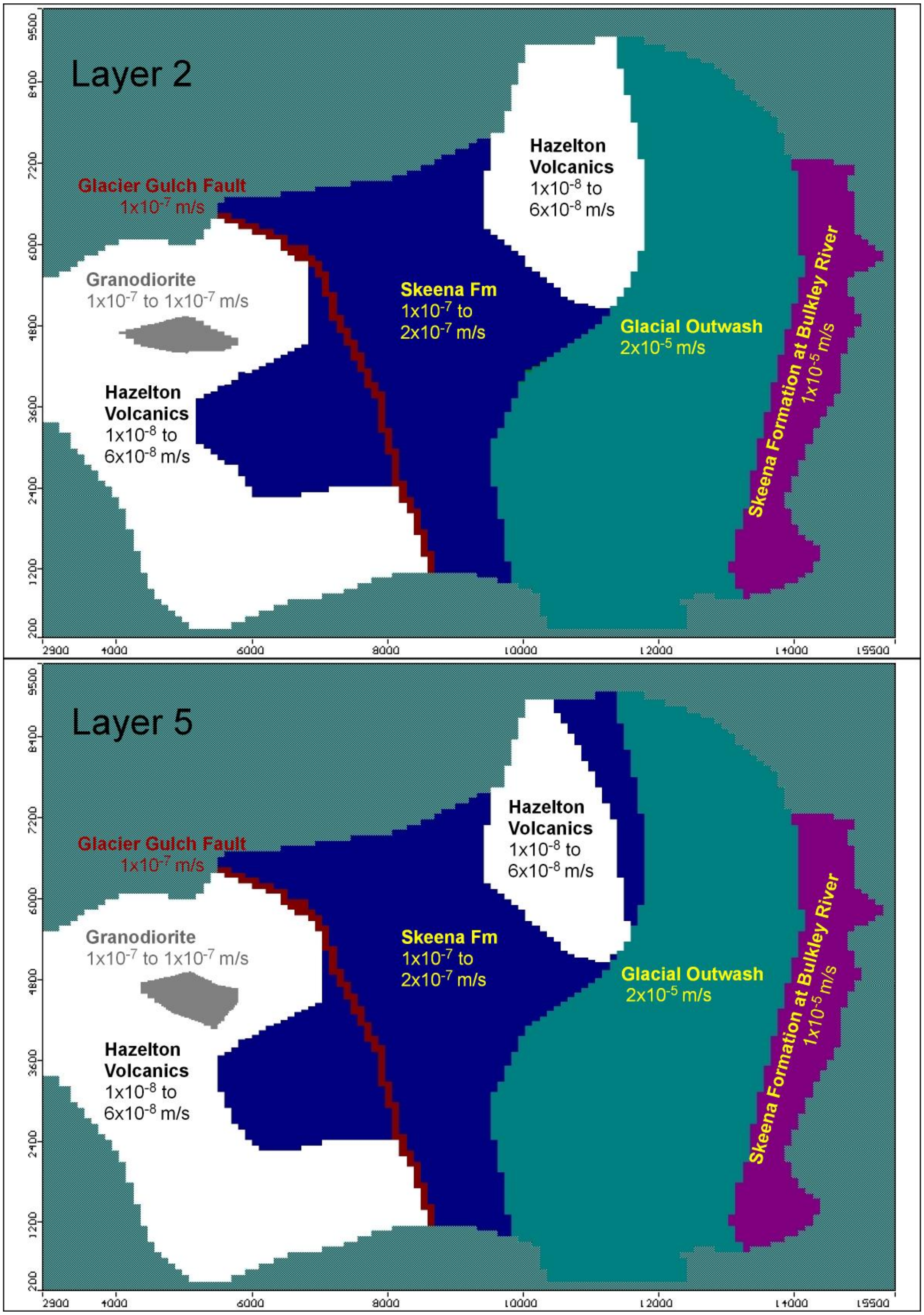
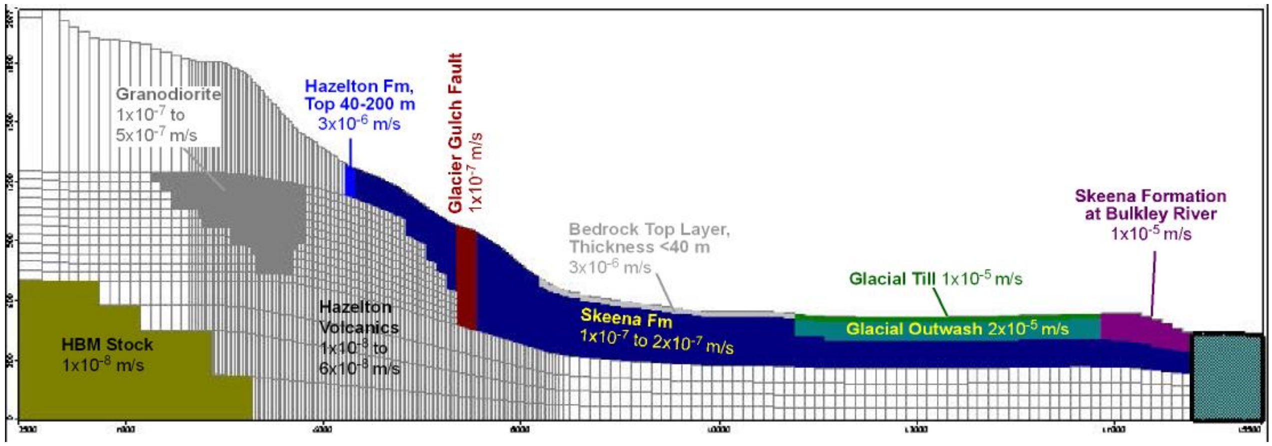


Figure 24. Second Calibration Hydraulic Conductivity Zones, Row 102, Granodiorite as Separate Unit, 2X Vertical Exaggeration



Steady-State Calibration to Current Conditions

The best-fit hydraulic conductivities when the granodiorite is treated as a separate unit are shown in Table 5. If a material is not listed in Table 5, it has the same value as from the First Calibration (Table 3). The heads calibration results for Calib 2 are shown in Figure 25, and the heads in Layer 3 are shown in Figure 26.

Table 5. Best-Fit Hydraulic Conductivity Values (m/s), Second Calibration, Calib 2

Material Property (all Isotropic)	Value
Hazelton Volcanics Hydraulic Conductivity (m/s)	$6x10^{-8}$
Skeena Rocks Hydraulic Conductivity (m/s)	$1x10^{-7}$
Granodiorite Rocks Hydraulic Conductivity (m/s)	$1x10^{-7}$
Calibration Statistics for All Wells	
Normalized Root Mean Squared Error (NRMSE)	4.4%
Residual Mean (m)	17
Calibration Statistics for Site Wells Only (DAV-1A, DAV-03, DAV-04, 700 Adit Pressure)	
NRMSE	6.7%
Residual Mean (m)	-3.4
Predicted Outflow at 1066 Adit (L/s)	11

Figure 25. Calibration Statistics, Calib 2

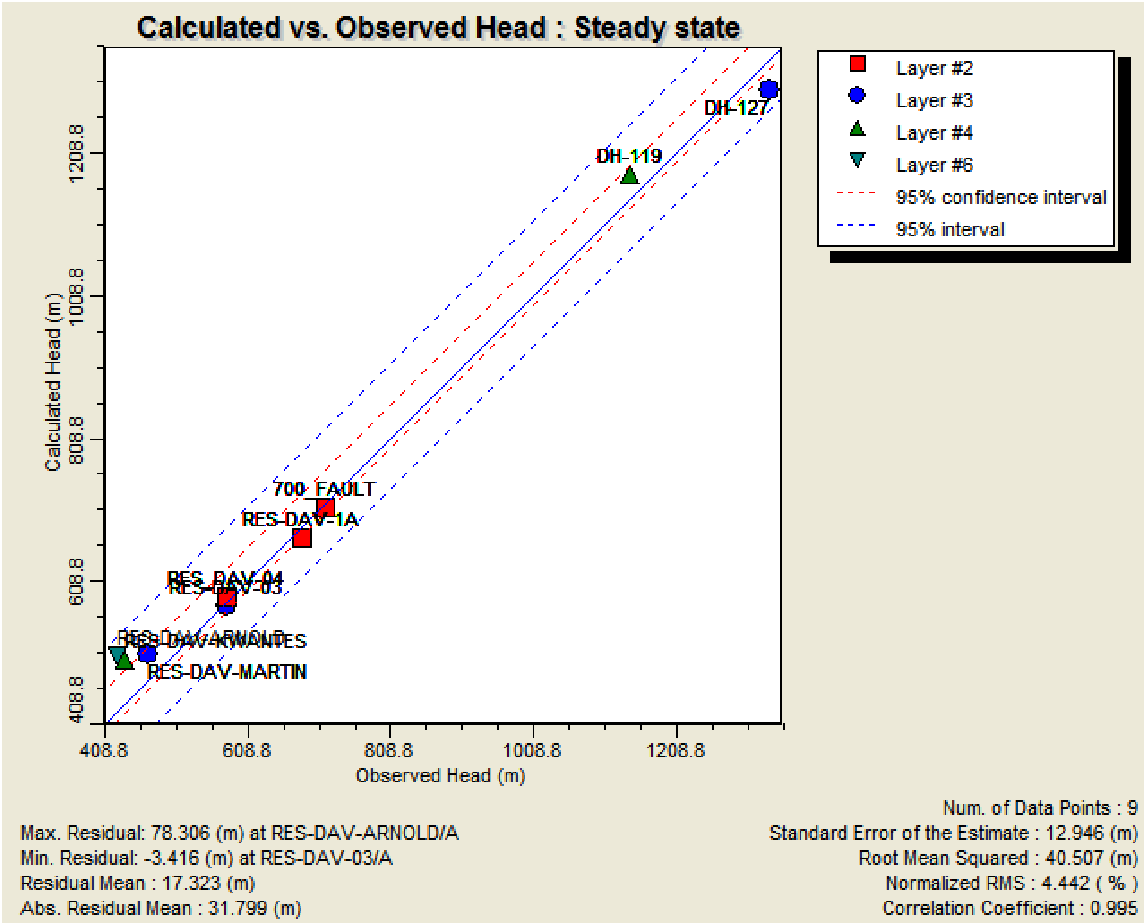
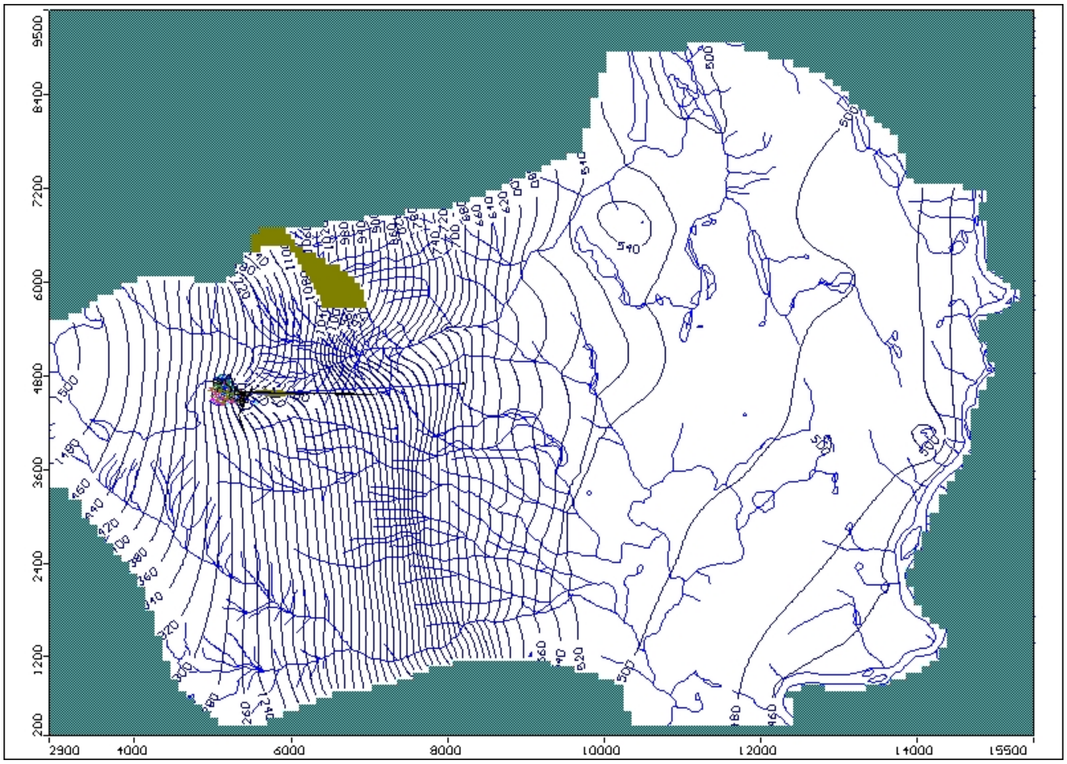


Figure 26. Predicted Heads in Layer 3, Calib2



Transient Simulations of 700 Adit Development and Mining

The predicted rate of groundwater discharge to the mine for Calib 2 is shown in Figure 27. A comparison of Figures 27 and 22 shows that, with the inclusion of a higher hydraulic conductivity granodiorite and a higher subglacial recharge rate, the predicted peak groundwater discharge to the adit and mine is higher. However, the predicted flows at the end of adit development and mine development are less than 25% higher, as shown in Table 6.

Figure 27. Predicted Mine Flows, Calib 2

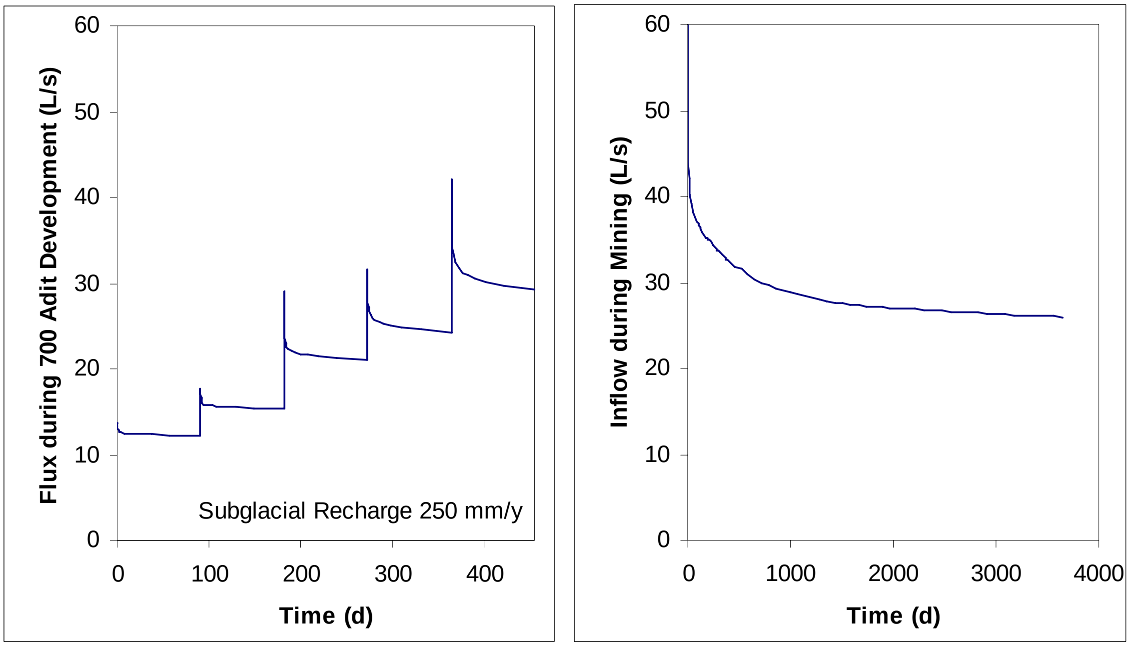


Table 6. Predicted Adit and Mine Flows (L/s) Calib 1 and Calib 2

Discharge Zone	Calib 1A	Calib 1B	Calib 2
Peak Modeled 700 Adit Flow[1]	35	29	42
Flow at end of Adit Development	25	27	29
Mine Flow 5-d into Mine Operation[2]	51	43	47
End of Mine Life Flow	21	22	26

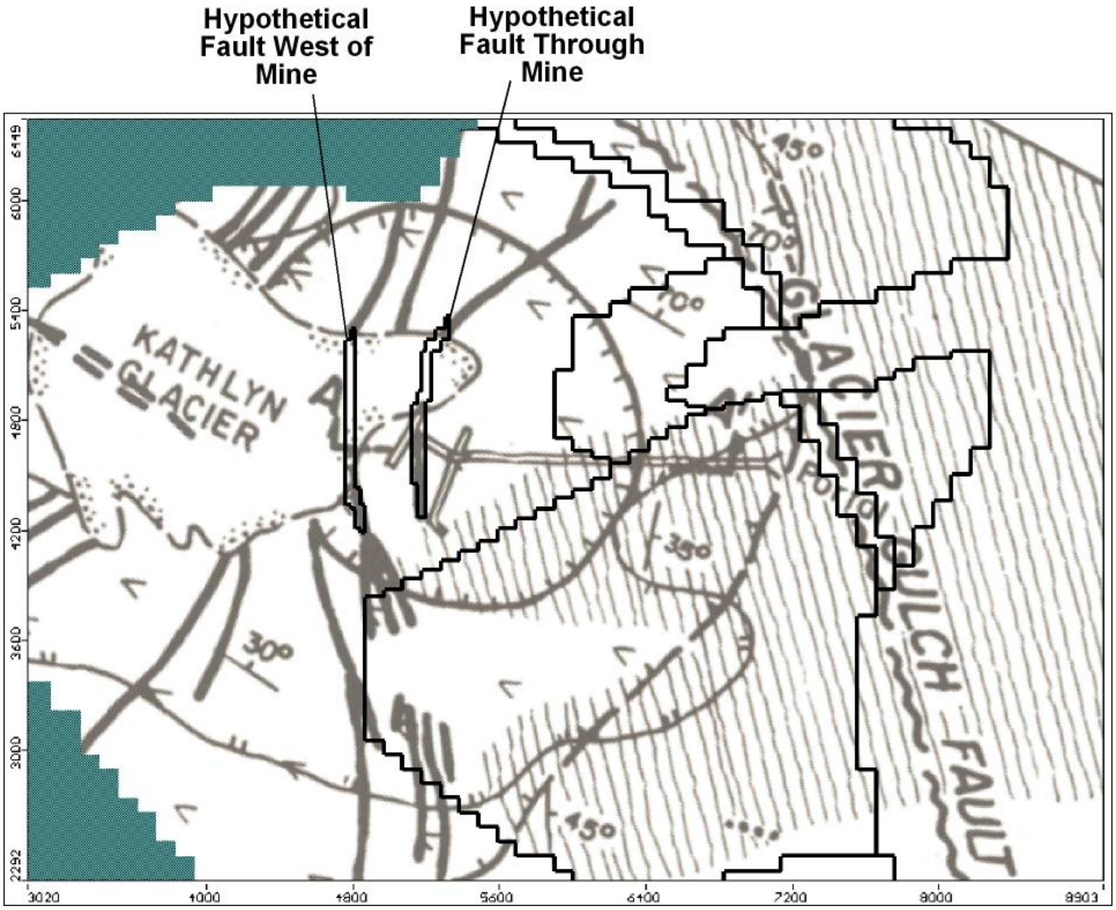
Note: [1]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[2]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining

Sensitivity to Faults Through Mine

It was demonstrated above that the presence of the Glacier Gulch Fault does not affect predicted groundwater discharge to the mine. Although the 700 Adit will cross this fault during mining, the expected hydraulic head encountered at the mine is expected to be relatively low, since the adit will intersect the top of the fault. However, it is possible that a significant transmissive fault encountered farther into the mountain could produce greater groundwater discharge to the mine. To examine this possibility, two fault zones were hypothesized to correspond to quartz dykes observed in the area (see Figure 28).

One of the two faults is assumed to intersect the mine. The other follows a quartz dyke west of the mine and is located under the Kathlyn Glacier and within the granodiorite material in the model. The faults were introduced to Layer 1 of the model.

Figure 28. Location of Hypothesized Mine Area Faults



The predicted groundwater discharge rates to the mine with a transmissive fault in the centre of the mine are shown in Figure 29. The figure shows no change in predicted flows during adit development, as would be expected. However, during mining, the predicted groundwater discharge rates are lower, because the presence of a high permeability material lowers the initial water table in this area. It is concluded that of a fault zone in the mine area will not significantly influence quasi-steady state groundwater discharge rates to the mine.

The predicted groundwater discharge rates to the mine when the fault is west of the mine are shown in Figure 30. A fault in this location—under the glacier and therefore subject to higher recharge rates than the fault through the mine—is noticeable. Both during adit development and mining, the predicted groundwater flows are higher when this fault is included in the model. The higher the hydraulic conductivity assigned to the fault, the higher the increase in flow. Nevertheless, the increase in flow is estimated to be no more than 6%.

Figure 29. Predicted Groundwater Discharge to Adit and Mine with Transmissive Fault Above Mine

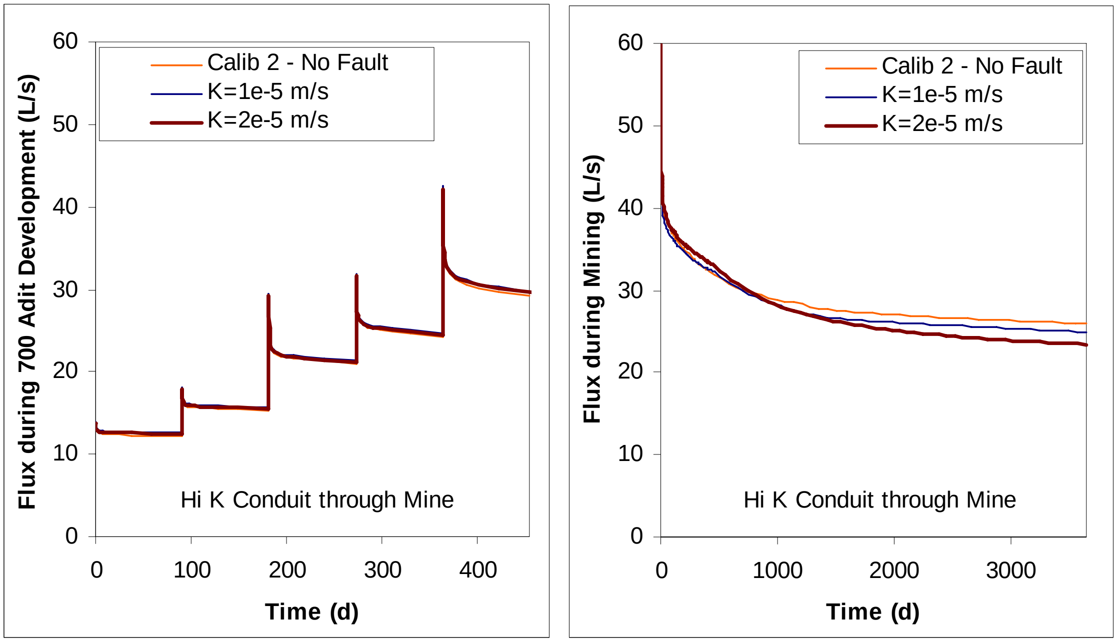
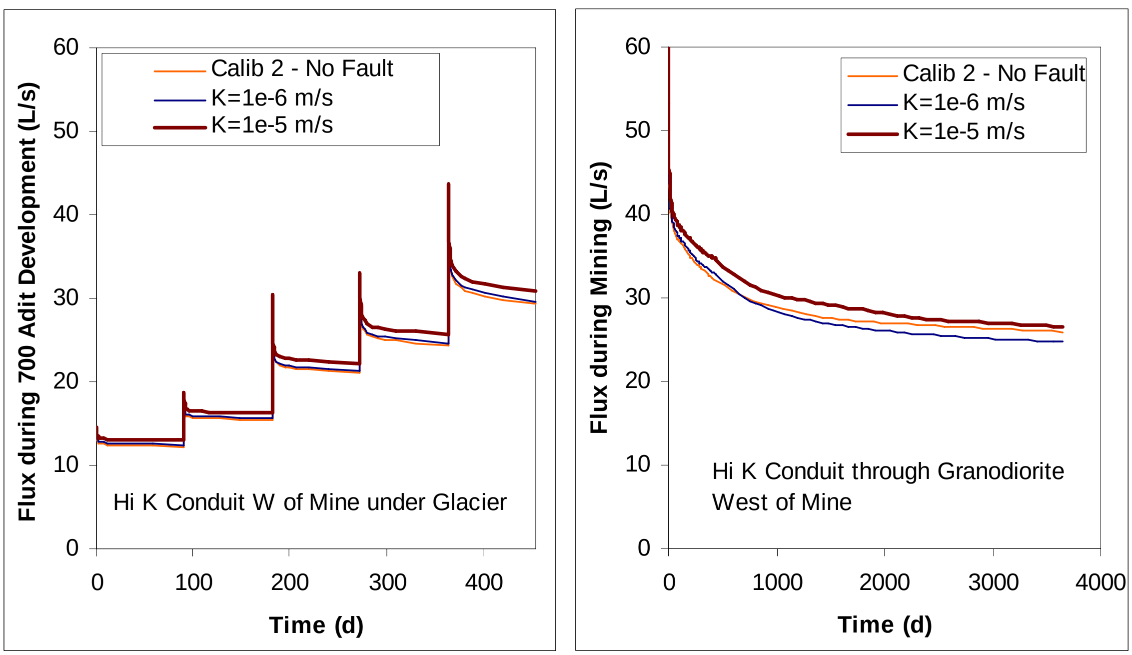


Figure 30. Predicted Groundwater Discharge to Adit and Mine with Transmissive Fault West of Mine



Sensitivity Analysis

Methodology

Up to now, the modeled parameter combinations have been selected to be those that meet the calibration targets—the observed heads and the groundwater flow measurements at the 1066 Adit. In this section, the results of a sensitivity analysis are presented. The sensitivity analysis used, as a starting point, the parameters for Calib 2. From this starting point, selected parameters were perturbed upward and downward such that the calibration targets were no longer met and/or the model predicted infeasible solutions (see discussion below for examples of an infeasible solution).

Hazelton Volcanics

The effect of varying the hydraulic conductivity of the Hazelton Volcanics was explored by raising it from the Calib 2 value of $6x10^{-8}$ m/s to $1x10^{-7}$ m/s and lowering it to $2x10^{-8}$ m/s. The hydraulic conductivity was lowered until the predicted groundwater discharge to the 1066 Adit was roughly doubled. The hydraulic conductivity was raised such that the mine was still saturated. In other words, raising the hydraulic conductivity of the Hazelton Volanics has the effect of flattening the water table. At a sufficiently high value, the relevant part of the mountain (i.e., in the vicinity of the mine) is dry in the model. Therefore, the hydraulic conductivity of the Hazelton Volcanics was increased by a factor of only 1.7 above the calibrated value.

Table 7. Results of Sensitivity Analysis, Hydraulic Conductivity of Hazelton Volcanics

	Low Hazelton K	Calib 2	High Hazelton K[1]
Hazelton Volcanics K (m/s)	$2x10^{-8}$	$6x10^{-8}$	$1x10^{-7}$
NRMSE – Site Wells	7.5%	6.7%	6.8%
Residual Mean (m) – Site Wells	-5.2	-3.4	-3.1
Calibrated 1066 Adit Flow (L/s)	19	11	5
Peak Modeled 700 Adit Flow (L/s)[2]	38	42	32
Flow at end of Adit Development (L/s)	33	29	24
Mine Flow 5-d into Mine Operation (L/s)[3]	56	47	n/a[4]
End of Mine Life Flow	27	26	n/a[4]

Notes: [1]The head convergence criterion was increased to 0.5 m for the initial condition in this run.
[2]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[3]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining
[4]Determining a lower-bound flux was deemed of secondary priority, and these transient runs were not completed.

The results of these runs are shown in Table 7. Raising the hydraulic conductivity has the effect of lowering the predicted groundwater discharge to the 1066 Adit, due to the lowering of the water table in Hudson Bay Mountain. It also reduces the predicted groundwater discharge to the mine by approximately 20% during development of the 700 Adit.

Conversely, lowering the hydraulic conductivity by a factor of three roughly doubles the predicted groundwater discharge to the 1066 Adit prior to mining. In addition, the predicted peak groundwater discharge rates to the mine and adits are a factor of 10% to 20% higher during mining. However, the ultimate quasi-steady value at the end of mining remains essentially unchanged.

Although the hydraulic conductivity of the Hazelton Volcanics is important from the perspective of the calibration, the predicted groundwater discharge rates to the mine are largely unchanged. Therefore, it is concluded that the calibrated value of this parameter is reasonable for this assessment.

Skeena Formation

In this sensitivity analysis, the hydraulic conductivity of the Skeena Formation was raised by a factor of ten to $1x10^{-6}$ m/s and lowered by a factor of five to $2x10^{-8}$ m/s. The results are summarized in Table 8. As for the Hazelton Volcanics, raising the hydraulic conductivity of the Skeena Formation lowers the water table in Hudson Bay Mountain and, consequently, reduces the predicted flows to the 1066 Adit and to the mine during operations. Predicted flows to the 700 Adit at the beginning of mining dropped from 29 L/s to 3 L/s.

Table 8. Results of Sensitivity Analysis, Hydraulic Conductivity of Skeena Formation

	Low Skeena K[1]	**Calib 2**	**High Skeena K**
Skeena K (m/s)	$2x10^{-8}$	$1x10^{-7}$	$1x10^{-6}$
NRMSE – Site Wells	4.9%	6.7%	8.2%
Residual Mean (m) – Site Wells	12	-3.4	-15
Calibrated 1066 Adit Flow (L/s)	19	11	1
Peak Modeled 700 Adit Flow (L/s)[2]	56	42	6
Flow at end of Adit Development (L/s)	40	29	3
Mine Flow 5-d into Mine Operation (L/s)	60	47	n/a[3]
End of Mine Life Flow	35	26	n/a[3]

Notes: [1]The interval between rewetting intervals was increased to 16 for the initial condition in this run.
[2]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[3]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining
[4]Determining a lower-bound flux was deemed of secondary priority, and these transient runs were not completed.

Lowering the Skeena Formation hydraulic conductivity has the effect of increasing the predicted groundwater discharge to the 1066 Adit and to the operating mine. However, the model predicts unreasonably high heads along the slopes of the mountain, with piezometric heads in excess of 100 m at the surface. So, although the model shows that reducing the hydraulic conductivity of the Skeena formation will result in higher predicted groundwater discharge rates in the adits and mine, the higher flows are the result of trying to force too much water into the mountain.

Therefore, it is concluded that the calibrated value of this parameter is reasonable for this analysis.

Surficial Bedrock

As indicated in Figure 7, the surficial Hazelton and Skeena formation layers were assigned a higher hydraulic conductivity than the lower layers. This was done to account for increased fracturing at surface. Two zones were designated, corresponding to differing thicknesses of the top layer. The results of a sensitivity analysis of these parameters are shown in Tables 9 and 10. As for the Hazelton Volcanics, the value of these parameters does not significantly affect the groundwater discharge predictions. Therefore, it is concluded that the calibrated values of these parameters are reasonable for this analysis.

Table 9. Results of Sensitivity Analysis, Hydraulic Conductivity of Surficial Bedrock (<40 m)

	Low K	Calib 2	High K[1]
Surficial Bedrock (<40 m) K (m/s)	$3x10^{-7}$	$3x10^{-6}$	$8x10^{-6}$
NRMSE – Site Wells	15%	6.7%	6.3%
Residual Mean (m) – Site Wells	19	-3.4	3.6
Calibrated 1066 Adit Flow (L/s)	13	11	13
Peak Modeled 700 Adit Flow (L/s)[2]	44	42	46
Flow at end of Adit Development (L/s)	36	29	33
Mine Flow 5-d into Mine Operation (L/s)[3]	53	47	50
End of Mine Life Flow	29	26	29

Notes: [1]The interval between rewetting intervals was increased to 16 for the initial condition in this run.
[2]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[3]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining

Table 10. Results of Sensitivity Analysis, Hydraulic Conductivity of Surficial Bedrock (40-200 m thick)

	Low K	Calib 2	High K[1]
Surficial Bedrock (40-200 m) K (m/s)	$6x10^{-8}$	$5x10^{-7}$	$5x10^{-6}$
NRMSE – Site Wells	6.6%	6.7%	6.5%
Residual Mean (m) – Site Wells	-3.2	-3.4	-3.0
Calibrated 1066 Adit Flow (L/s)	12	11	13
Peak Modeled 700 Adit Flow (L/s)[2]	44	42	45
Flow at end of Adit Development (L/s)	31	29	32
Mine Flow 5-d into Mine Operation (L/s)[3]	49	47	n/a[4]
End of Mine Life Flow	27	26	n/a[4]

Notes: [1]The interval between rewetting intervals was increased to 16 for the initial condition in this run.
[2]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[3]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining
[4]Determining a lower-bound flux was deemed of secondary priority, and these transient runs were not completed.

Granodiorite

Of all the hydraulic conductivities, that of the granodiorite zone within Hudson Bay Mountain had the greatest effect on the predicted groundwater discharge rates to the mine. Unlike the other bedrock units, changing the hydraulic conductivity of the granodiorite does not have a large effect on the head calibration statistics or on the head distribution (i.e., does not create saturated zones at surface or lead to the drying out of mine area rocks). The hydraulic conductivity of the granodiorite, furthermore, has a significant effect on groundwater flow, both to the existing 1066 Adit and to the proposed adit and mine. A range of values for this parameter were tested in the model, as summarized in Table 11 and Figure 31. This range of value is less than the range of $4x10^{-9}$ m/s to $1x10^{-5}$ m/s determined via packer testing of drillholes. However, the Calib 2 value of $1x10^{-7}$ m/s is approximately equal to the geometric mean value ($1.4x10^{-7}$ m/s) and median value ($1.3x10^{-7}$ m/s) of the packer tests. GD3 uses a hydraulic conductivity that is approximately equal to the arithmetic mean of the measured values ($1.1x10^{-6}$ m/s), but still higher than the upper quartile value ($3.5x10^{-7}$ m/s). GD4 has a still higher hydraulic conductivity of $2x10^{-6}$ m/s.

For this range of values, $1x10^{-8}$ m/s to $2x10^{-6}$ m/s, the predicted flow to the 1066 Adit ranges from 5 L/s to 26 L/s. The predicted peak groundwater discharges rates during 700 Adit development range from 35 L/s to 52 L/s. The predicted groundwater flow to the mine at the end of mining ranges from 18 L/s to 38 L/s.

Table 11. Results of Sensitivity Analysis, Hydraulic Conductivity of Granodiorite

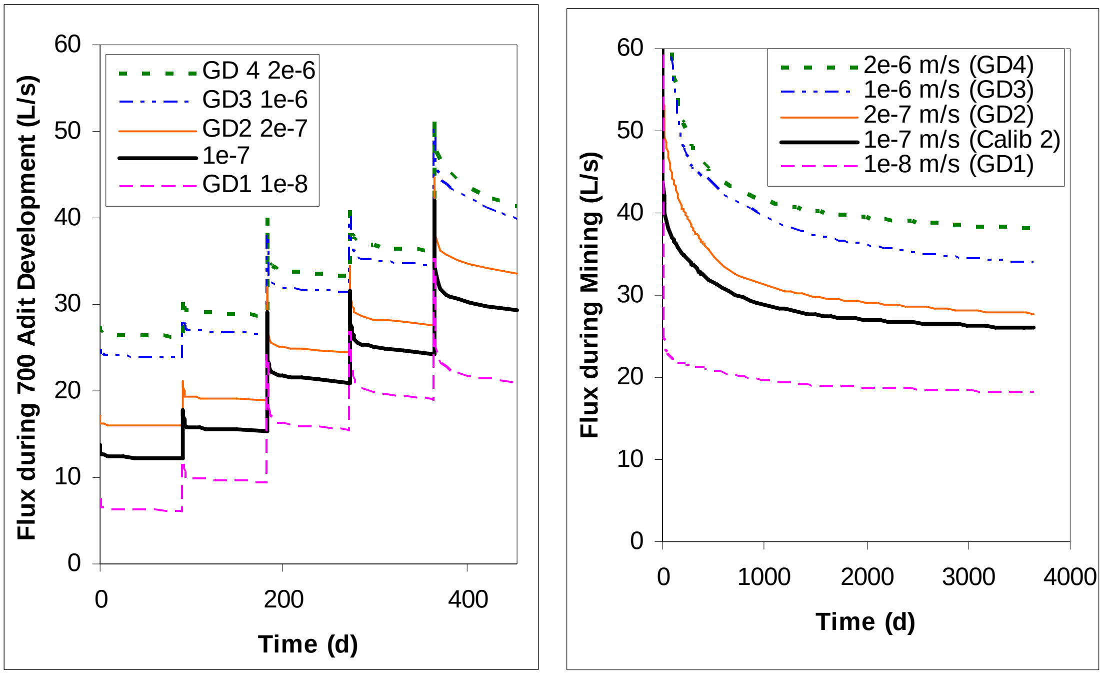
	GD1	Calib 2	GD2	GD3[1]	GD4[1]
Granodiorite K (m/s)	$1x10^{-8}$	$1x10^{-7}$	$2x10^{-7}$	$1x10^{-6}$	$2x10^{-6}$
NRMSE – Site Wells	6.5%	6.7%	6.9%	7.4%	7.6%
Residual Mean (m) – Site Wells	-3.0	-3.4	-3.5	-4.5	-4.9
Calibrated 1066 Adit Flow (L/s)	5	11	15	23	26
Peak Modeled 700 Adit Flow (L/s)[2]	35	42	45	50	52
Flow at end of Adit Development (L/s)	21	29	34	40	41
Flow 5-d into Mine Operation (L/s)[3]	26	47	57	100	130
End of Mine Life Flow	18	26	28	34	38

Note: [1]The head convergence criterion was increased to 0.6 m for the initial condition in these runs.
[2]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[3]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining

The groundwater discharge observed in the 1066 Adit to date has not been anywhere near 26 L/s. Therefore, the results of GD4 are considered overly conservative. Even so, the predicted typical groundwater discharge rates during operation are approximately 40 L/s for this simulation.

It is also informative to look at the predicted flows five days after all the mine drains are activated in the model. These fluxes range from 26 L/s to 130 L/s for the simulations summarized in Table 11. The significance of these values is discussed further below in the Discussion section.

Figure 31. Predicted Groundwater Discharge to Adit and Mine, Sensitivity to Granodiorite K



<u>Recharge</u>

In assessing the potential range of mine discharge to the mine and adits, the recharge value was raised to evaluate an upper bound of recharge. First, the overall recharge rates (i.e., recharge in Zones 1, 3 and 4 of Figure 6) was increased from 150 to 200 mm/year. Doing this resulted in significant saturated zones at the edge of the valley, with standing water in excess of 15 m at the base of the slope. In other words, the recharge rate could not be reasonably increased given the hydraulic parameters. Secondly, the recharge rate under the Kathlyn Glacier was increased to a value of 600 mm/year, considered to be a maximum possible recharge rate, given the annual average precipitation in the area.

The predicted flows to the adit and mine during pre-development and mining are shown in Figure 32. It can be seen that increasing the modeled average recharge rate can have a significant impact on the groundwater flows to the adit and mine.

Figure 32. Predicted Groundwater Discharge Rates to Adits and Mine, Sensitivity to Modeled Recharge Rate

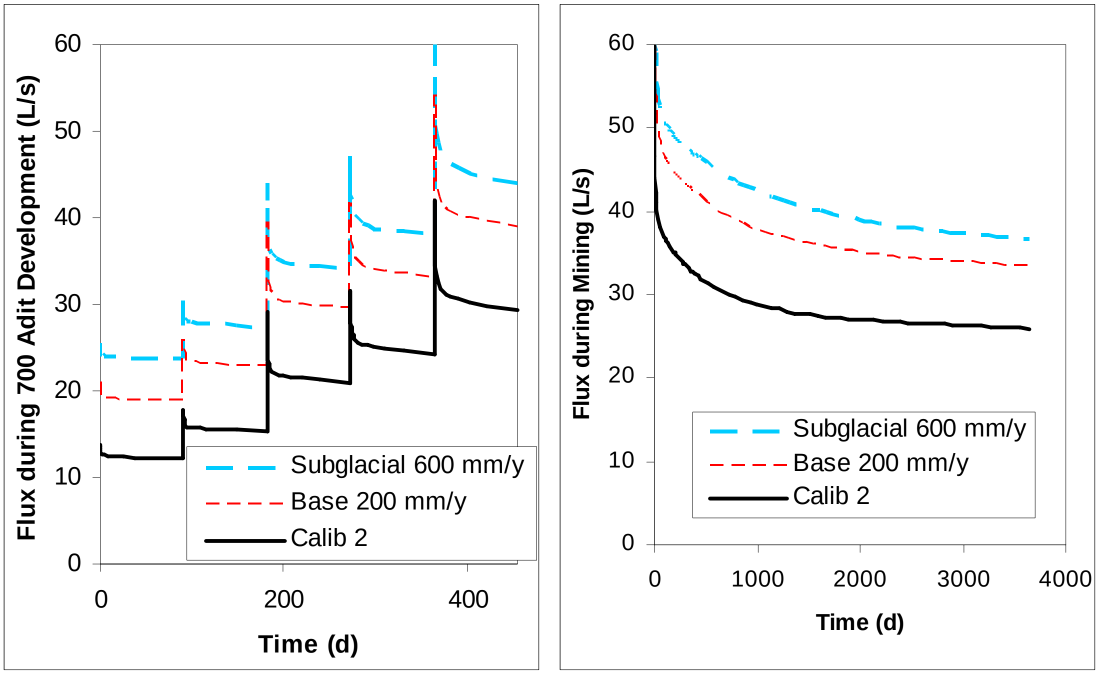


Table 12. Results of Sensitivity Analysis, Recharge Rate

	Calib 2	Raise Base Recharge[1]	Raise Subglacial Recharge
Base Recharge (mm/y)	150	200	150
Subglacial Recharge (mm/y)	250	250	600
NRMSE – Site Wells	6.7%	5.8%	6.1%
Residual Mean (m) – Site Wells	-3.4	0.3	-1.7
Calibrated 1066 Adit Flow (L/s)	11	17	22
Peak Modeled 700 Adit Flow (L/s)[2]	42	54	62
Flow at end of Adit Development (L/s)	29	39	44
Mine Flow 5-d into Mine Operation (L/s)[3]	47	58	64
End of Mine Life Flow	26	34	37

Note: [1]The interval between rewetting intervals was increased to 16 for the initial condition in this run.
[2]Peak flow calculated 1.4 hours after the last 3-month stage in the adit simulation.
[3]Mining Simulation assumes the entire mine becomes a groundwater drain on Day 1 of mining

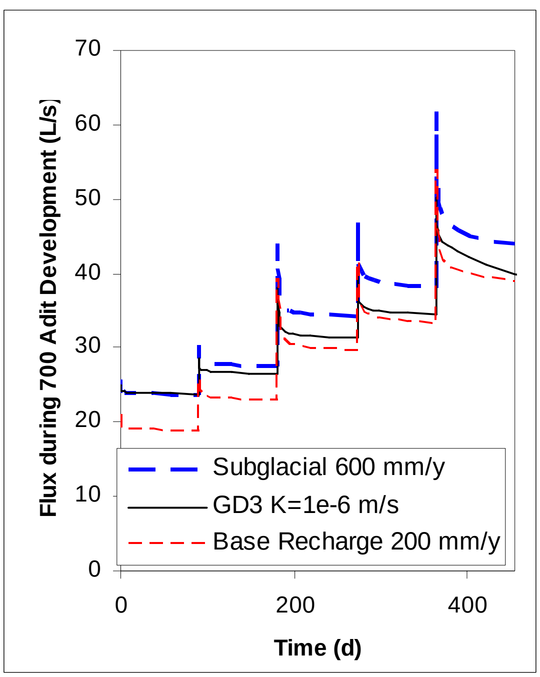
Estimated Upper Bound Groundwater Discharge to Mine and Adits

Given the observed average groundwater flow to the 1066 Adit of approximately 12 L/s, estimates of discharges made using parameter combinations where the simulated current 1066 Adit inflow of twice that volume could be considered a reasonable upper bound mine discharge. The results of three upper bound simulations, each associated with the increase of a different parameter, are shown in Table 13. Although the predicted discharge when the base recharge was raised to 200 mm/y did not result in a doubling of the 1066 Adit, this value was not further increased because of simulated saturation at surface, as discussed above.

Table 13. Upper Bound Groundwater Discharge Estimates from Sensitivity Analysis

	Base Recharge 200 mm/y	Subglacial Recharge 600 mm/y	Granodiorite K 1x10^{-6} m/s GD3
Calibrated 1066 Adit Flow (L/s)	17	22	23
Upper Bound Typical Flow to Adits and Mine			
End of 700 Adit Development (L/s)	39	44	40
End of Mine Life (L/s)	34	37	34
Upper Bound Peak Flow Estimate Assuming 700 Adit Created in 3-Month Increments			
Peak Modeled 700 Adit Flow (L/s)	54	62	50

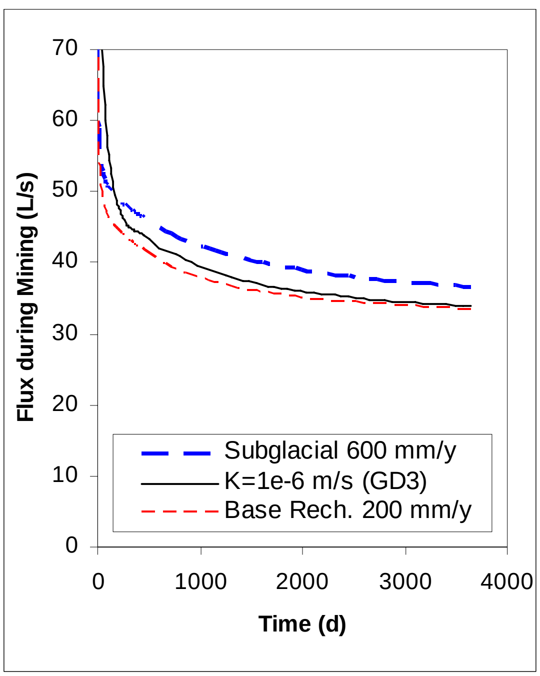
Figure 33. Predicted Groundwater Discharge to Adits, Upper Bound Simulations



As shown in Figure 33, the model predicts that during development of the 700 Adit, the peak groundwater discharge rates—even under the assumption that the entire length of the adit to be developed in any three month period begins to accept groundwater discharge at the beginning of that three month period—are less than 60 L/s except for the few hours at the beginning of the last period of the simulation that had an extremely high subglacial recharge rate of 600 mm/year.

There are, on the other hand, much higher predicted flows in the mining simulations shown in Figure 34. Recall that these simulations assume that the dewatering of the entire mine footprint begins on Day 1 of mining and also assume that there will be no backfilling of mined-out stopes. Of course, the entire mine will not be operational on Day 1 of operations, and the entire mine will not operate as a drain. As noted in the Methodology section, the transient mining simulations, with their exceedingly conservative assumption that the entire mine starts draining on Day 1, were completed because the end-of-mine life groundwater flow estimates from the transient runs were 0.2 times to four times greater than the steady state results, depending on the hydraulic parameters used in the simulation. Therefore, they were not designed to be reasonable estimates of the groundwater inflow to the mine during operations. Nevertheless, this Worst Case analysis indicates that, although short-term peak groundwater flows to the mine can be expected, end of mine life flows are less than 40 L/s.

Figure 34. Predicted Groundwater Discharge to Mine, Worst-Case Simulations



Given the exceedance of the design flow using these worst-case simulations, a final set of sensitivity runs were carried out such that only lowermost set of drains shown in Figure 5 was activated at the start of mining. This set of drains is located at an elevation of 1008 masl. Figure 35 shows that the groundwater discharge to the mine decreases more rapidly when only one section of the mine, albeit the section located at the greatest depth below the water table, is allowed to drain at a time. Table 14 shows the predicted fluxes in these runs. The table indicates that groundwater discharge rate exceeding 60 L/s will likely last for less than 10 days, even under the assumption of a significant volume of high permeability rock in the mine area. For this simulation, the model predicts an excess of 960 m^3 of water will be produced during the exceedance period.

Figure 35. Predicted Groundwater Discharge to Mine, Upper Bound Simulations

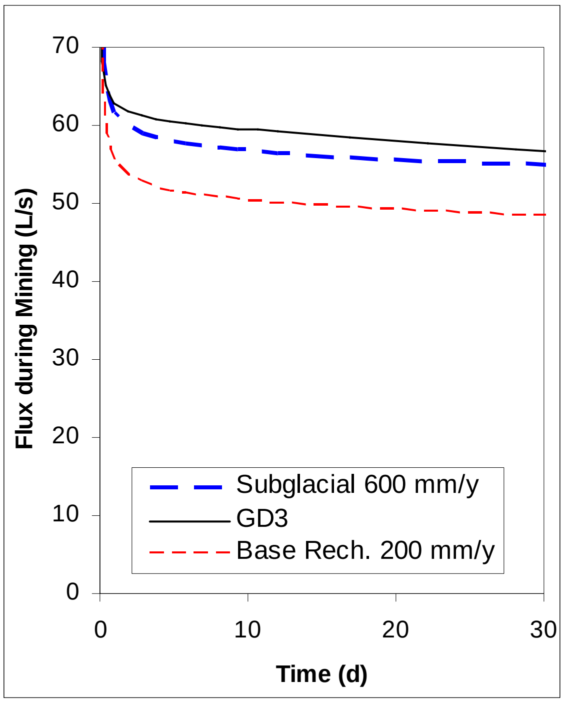


Table 14. Upper Bound Groundwater Discharge Estimates into Mine (With 1008 m drains operational)

Parameter	Base Recharge 200 mm/y	Subglacial Recharge 600 mm/y	Grano-diorite K $1x10^{-6}$ m/s GD3	Grano-diorite K $2x10^{-6}$ m/s GD4
Flow 5-d into Mine Operation (L/s)	52	58	61	61
Duration of Flows >60 L/s (days)	0.2	1	7	9
Volume of Water in Excess of 60 L/s (m^3) During Period of Excess	310	500	860	960

Predicted Effect of Mining on Steamflows

Table 15 summarizes the groundwater discharge rates to streams for the calibration runs. There is not much difference in the predicted pre-mining groundwater discharge rates to the creeks among the three runs.

Table 15. Predicted Groundwater Discharge Rates (L/s)

Discharge Zone	Calib 1A	Calib 1B	Calib 2
Kathlyn Creek	7	7	7
Kathlyn Tributary A	19	20	21
Kathlyn Tributary A3	4	4	4
Glacier Gulch Upper	13	19	20
Glacier Gulch Lower	29	29	29
Club Creek	12	12	12
Simpson Creek	38	52	37
Bulkley River	320	460	530

During mining, the model predicts reductions in the groundwater discharge to four of the creek zones. The percent reductions are tabulated in Table 16.

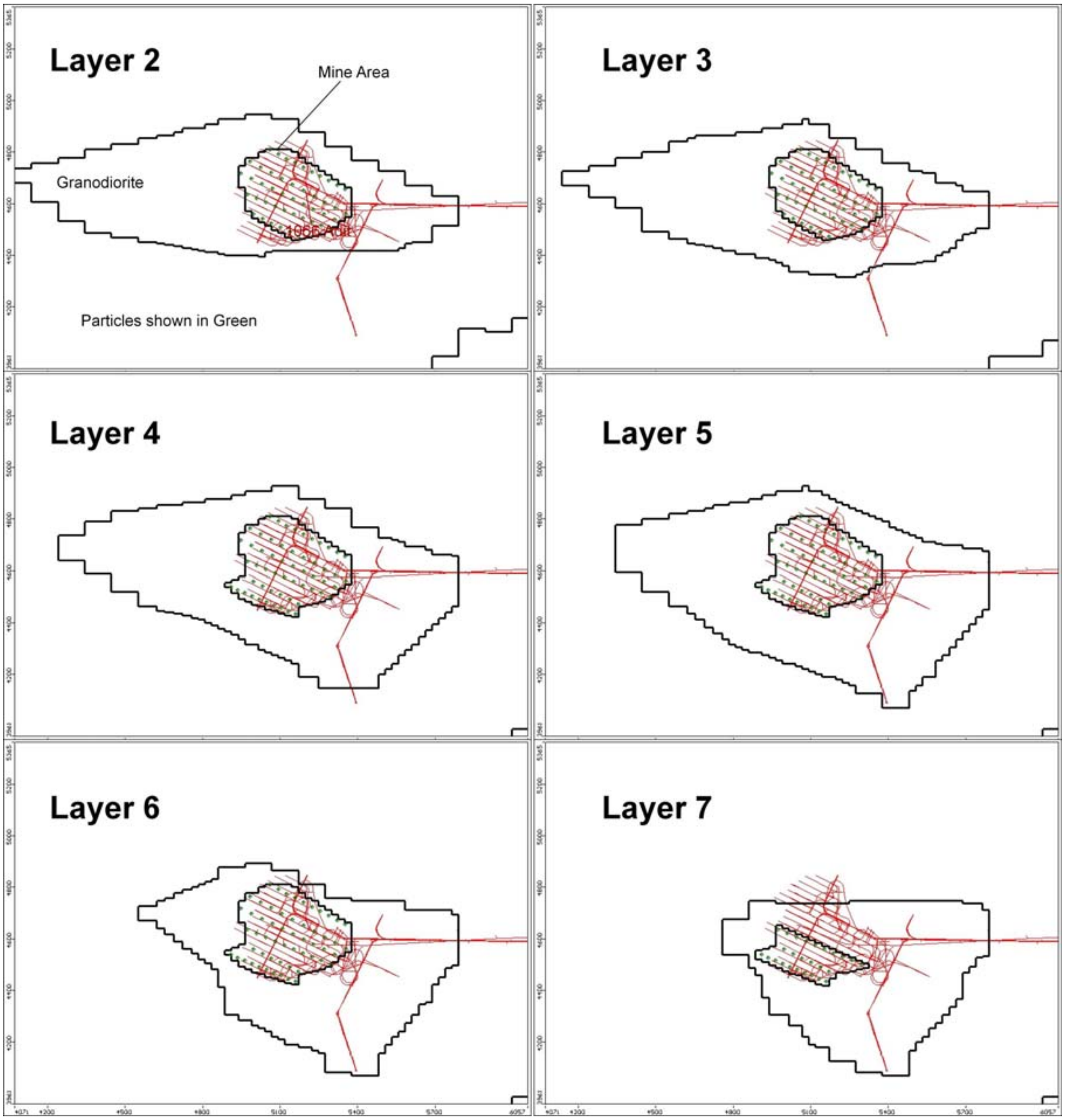
Table 16. Predicted Change in Groundwater Discharge to Affected Creeks

Discharge Zone	Calib 1A	Calib 1B	Calib 2
Kathlyn Creek	-1%	-3%	-4%
Kathlyn Tributary A	-1%	-4%	-3%
Kathlyn Tributary A3	-3%	-12%	-10%
Glacier Gulch Upper	-5%	-18%	-15%

Post-Mining Water Table Rebound

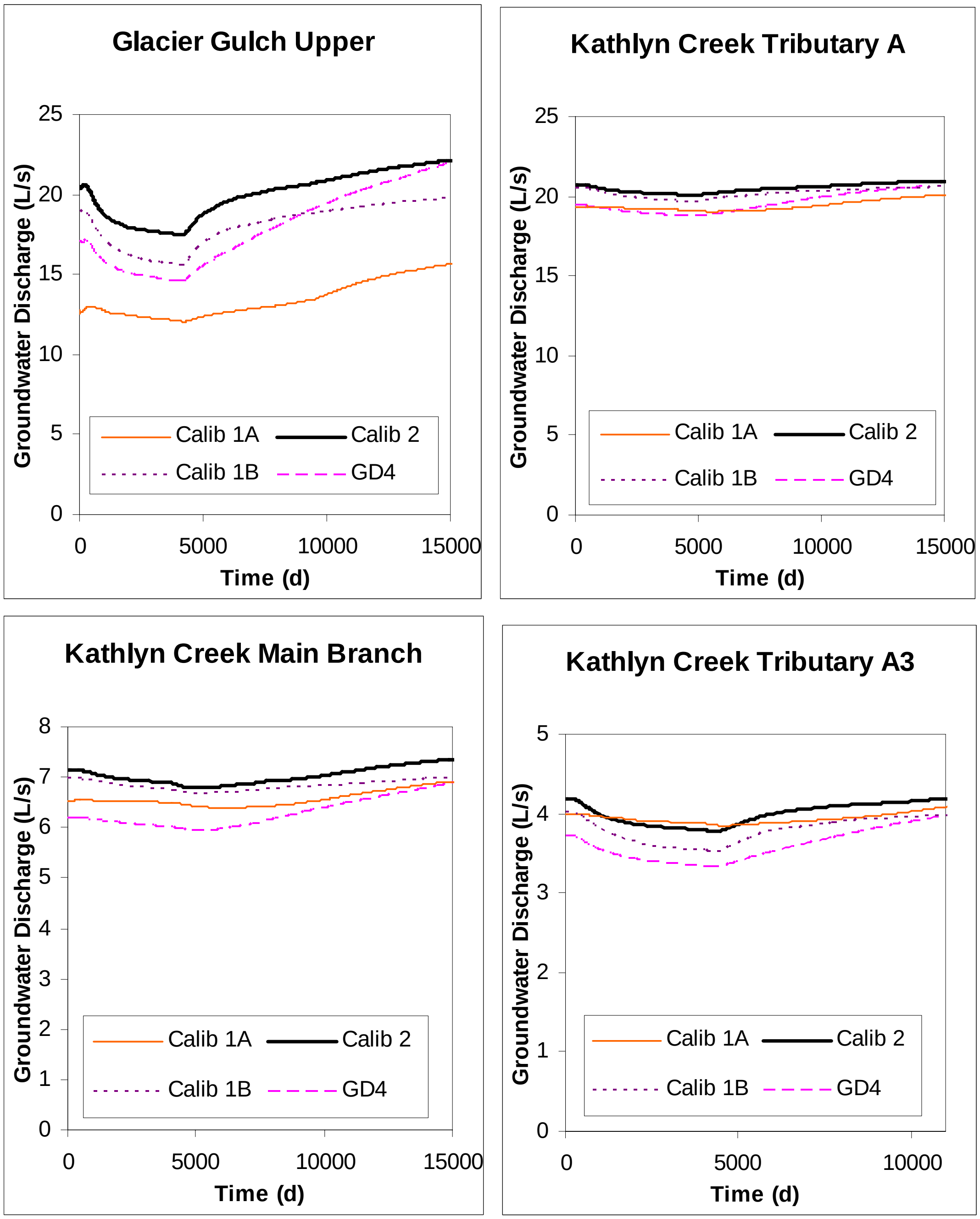
Transient simulations were completed to evaluate the water table rise after the cessation of mining. In these simulations, all drains in the 700 and 1066 Adits were deactivated, as were the drains in the mine itself. The post-closure mine will have different hydraulic properties than are present today. To simulate these changes, the effective hydraulic conductivity of the mined out area was raised to $1x10^{-5}$ m/s. The mine itself will be a network of juxtaposed backfilled areas, with low hydraulic conductivity, and of unfilled areas, with extremely high hydraulic conductivity. Because the model grid is not fine enough to resolve individual stopes, a bulk value of $1x10^{-5}$ m/s was selected. This is more than two orders of magnitude greater than the Hazelton rocks surrounding the mine. The post-closure mine's specific storage was kept at the pre-mining value of $5x10^{-6}$ m^{-1}, and the specific yield and porosity were increased to 0.2. The storage properties, including specific yield, will be important only in the transient simulations. The zone of higher hydraulic conductivity is shown in Figure 36.

Figure 36. Hydraulic Property Zones and Particles for Post-Closure Assessment



It is known that approximately 12 L/s of groundwater discharge is reporting to the 1066 Adit. Once this adit is sealed, this amount of water will discharge elsewhere, most likely via the nearby creeks. Figure 37 shows the predicted changes in groundwater discharge to the four zones in the model (see Table 16) that were most affected by mining. For comparison, the results for run GD4, with the highest granodiorite hydraulic conductivity, are included. The results show that the reduction in the groundwater baseflow component of streamflow in these four creeks could drop by as much as 18% during mining. On the other hand, they are expected to receive higher groundwater baseflow contributions after closure. The degree to which the streamflows increase is greater for the simulations that have a high hydraulic conductivity in the mine area.

Figure 37. Predicted Groundwater Discharge to Creeks, During and After Operations



For all the four cases shown in Figure 37, the groundwater discharge rates had returned to within 3% of their pre-mining value within 10 years of the end of mining. Eventually, the groundwater flow contribution to these creeks will return to levels observed prior to the drilling of the 1066 Adit in the 1960s.

Post-Closure Pathline Assessment

Methodology

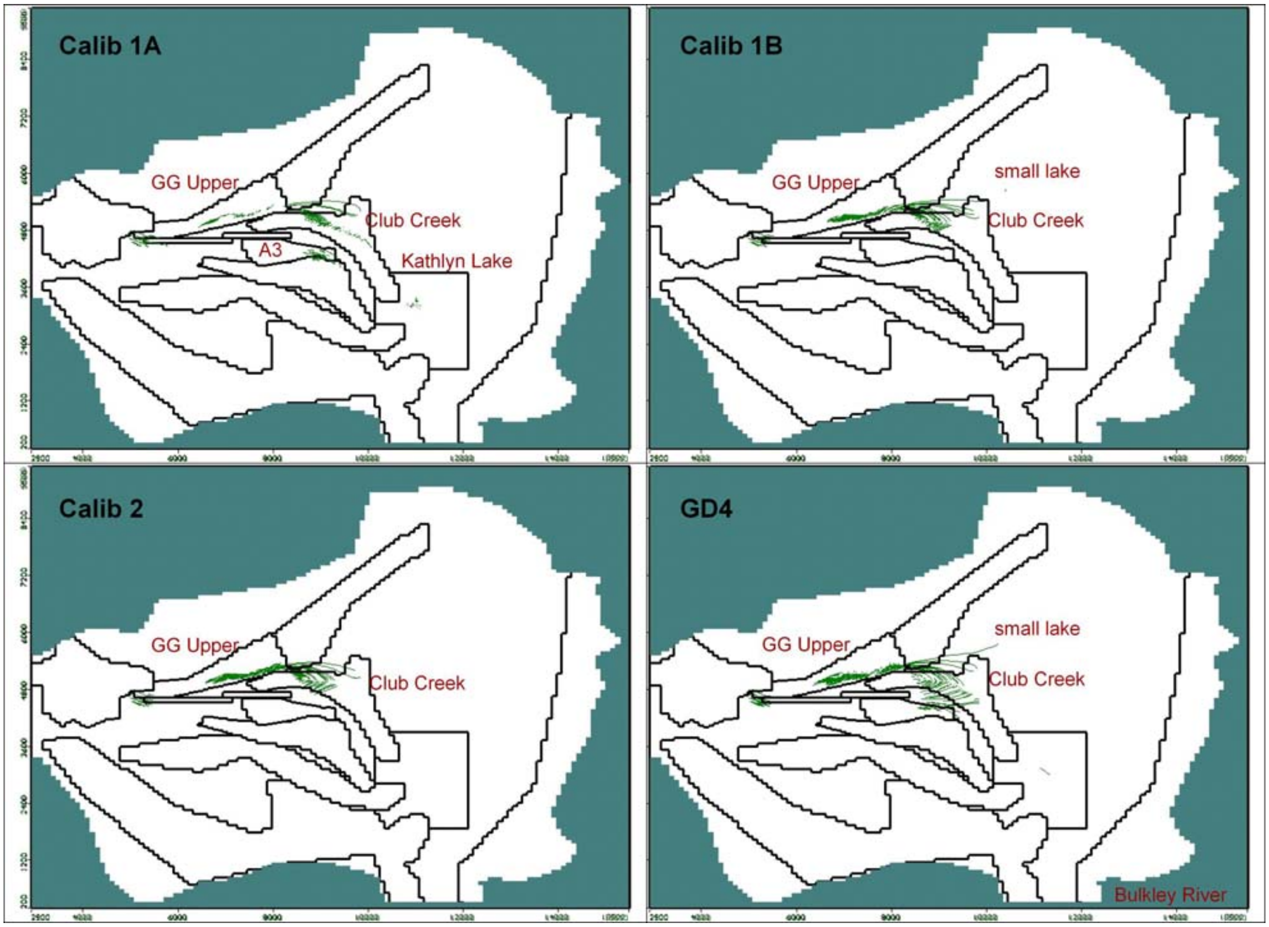
During operation, the mine will function as a significant groundwater sink. Therefore, groundwater flow from the mine to receptors will not occur. After mining, however, groundwater flow lines will pass through the mine. Therefore, downgradient impacts on groundwater and surface water are possible. The potential effect of the post-closure mine were evaluated using particle tracking with MODPATH.

Results

Figure 38 shows the endpoints of the steady state particles introduced into the mine at locations shown in Figure 36. For the most part, the particles travel to Glacier Gulch Creek and Club Creek, where they discharge to surface water. In some of the simulations, there was some particle migration to Kathlyn Creek Tributary A3, a small lake east of Glacier Gulch Creek, Lake Kathlyn and/or the Bulkley River. In all cases, the particles reach these groundwater discharge points at least 20 years after closure.

Although the particle tracking exercise cannot be used to predict concentrations, it can be used to identify the key receptors to groundwater which has flowed through the post-closure mine. It is clear that Club Creek, located downhill from the mine, and Glacier Gulch Creek, located in close vicinity to the mine, will receive the greatest impact from the post-closure mine.

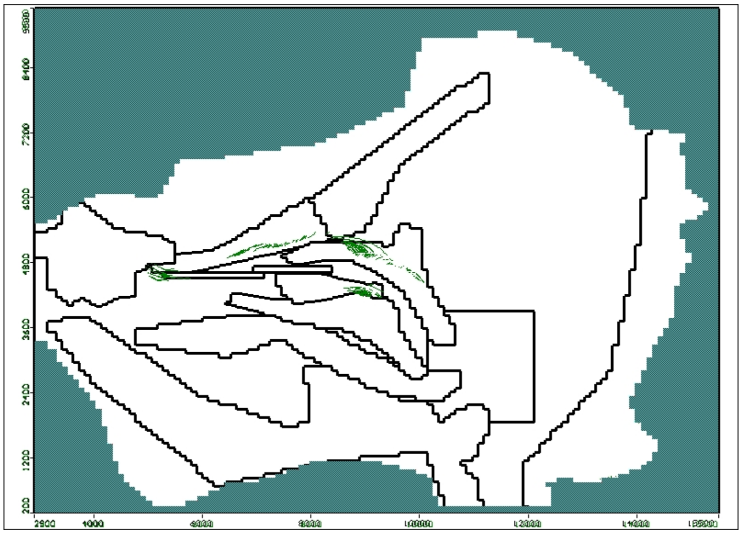
Figure 38. Pathline Endpoints From Particle Tracking Simulations, Calibration Runs and Worst-Case Hydraulic Parameters (GD4)



Sensitivity to Glacial Till Hydraulic Conductivity

A final sensitivity analysis was conducted on the hydraulic conductivity of the till layer underlying Lake Kathlyn. As indicated in Table 3 the horizontal hydraulic conductivity of this material is $1x10^{-5}$ m/s in the calibration runs. Additional runs were conducted in which the isotropic hydraulic conductivity of this material was set to values of $1x10^{-6}$ m/s, $1x10^{-7}$m/s and $1x10^{-8}$m/s. The pathline endpoints for the $1x10^{-7}$ m/s runs are shown in Figure 39. This figure shows that the effect of reducing the hydraulic conductivity of the modeled till layer is to deflect pathlines that end up in Lake Kathlyn to the Bulkley River. The hydraulic conductivity of the till, however, has a significantly reduced effect on the pathlines that discharge to Glacier Gulch Creek, and groundwater from the mine area continues to discharge to these streams, even for till hydraulic conductivities of $1x10^{-7}$m/s and $1x10^{-8}$m/s.

Figure 39. Pathline Endpoints From Particle Tracking Simulations, Calib 1A Parameters with Till Hydraulic Conductivity Reduced to Isotropic Value of 1x10^{-7} m/s



In the simulations presented above, a value of 1x10^{-6} m/s was selected, because it was considered the most conservative value. It was conservative because the dilution available in Lake Kathlyn and creeks near the mine will be less than that available within the Bulkley River.

Transport Simulations

Additional Calibration (to Fluxes at Glacier Gulch Creek)

As described in Appendix C4 of the EA Application, the water currently discharging from the 1066 Adit has a relatively constant geochemical signature, which includes elevated molybdenum and arsenic concentrations. It is expected that this geochemical signature is characteristic of the entire granodiorite zone. A geochemical review of available water quality data from the 1066 Adit and from Glacier Gulch Creek indicates that surface water in the upper reaches of Glacier Gulch Creek (GG1, located above existing the 1066 Adit discharge) is influenced by groundwater with this geochemical signature. By comparing sulphate ratios between the 1066 Adit water (assumed to be representative of the granodiorite zone) and GG1, it was estimated that 15% to 30% of the baseflow water sampled at GG1 is reflective of the granodiorite rock. Similarly, groundwater from the granodiorite accounts for ~40% of the baseflow water sampled at GG4. This suggests that the granodiorite zone is larger than assumed in Calib 2 and shown in Figures 23, 24 and 36. A slight increase in the granodiorite zone was required to calibrate model fluxes such that 15-30% of granodiorite-influenced water was simulated at GG1 and 40% at GG4. The enlarged granodiorite zone is shown in Figures 40 and 41.

Figure 40. Enlarged Granodiorite Area for Transport Simulations, Layers 2 to 11

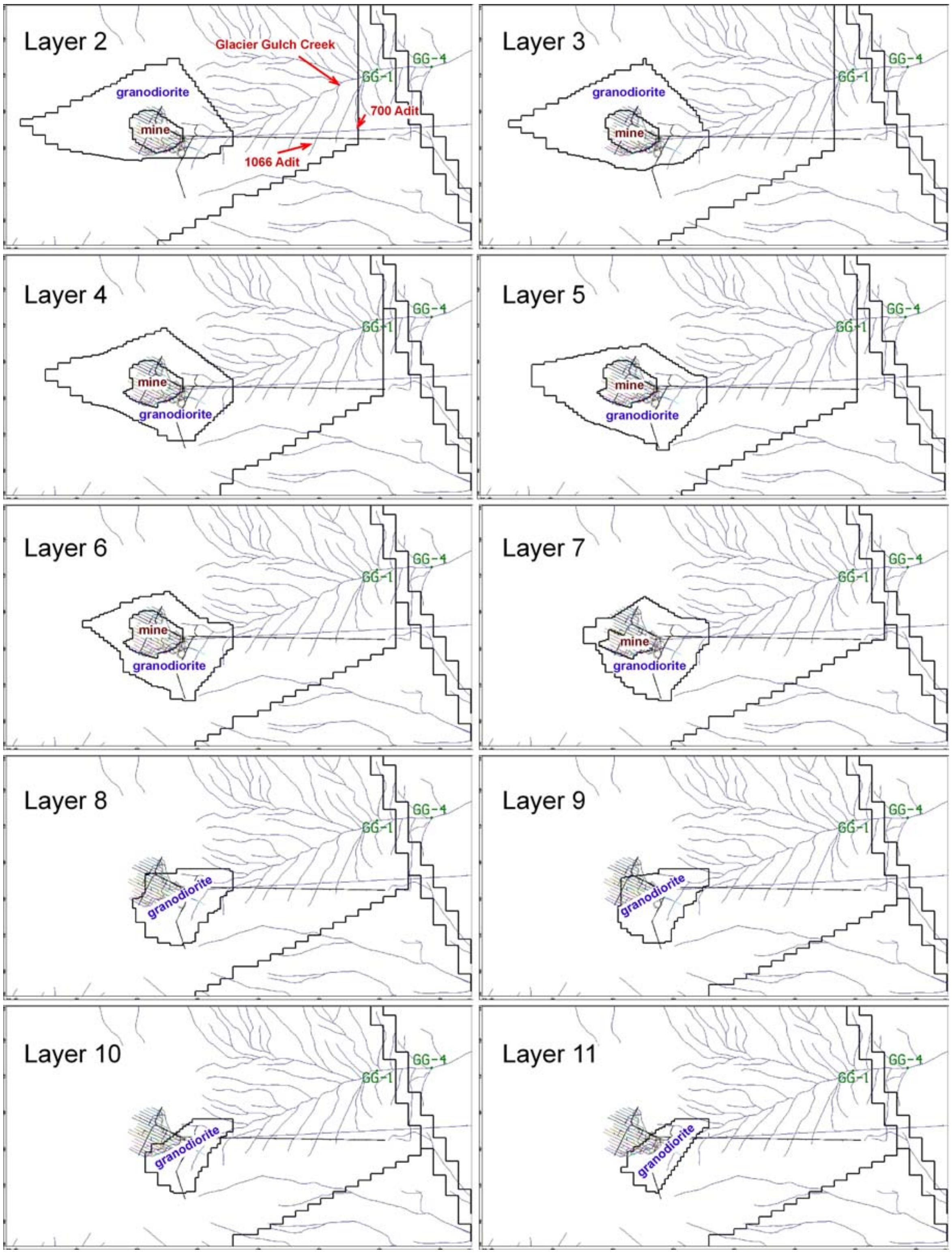
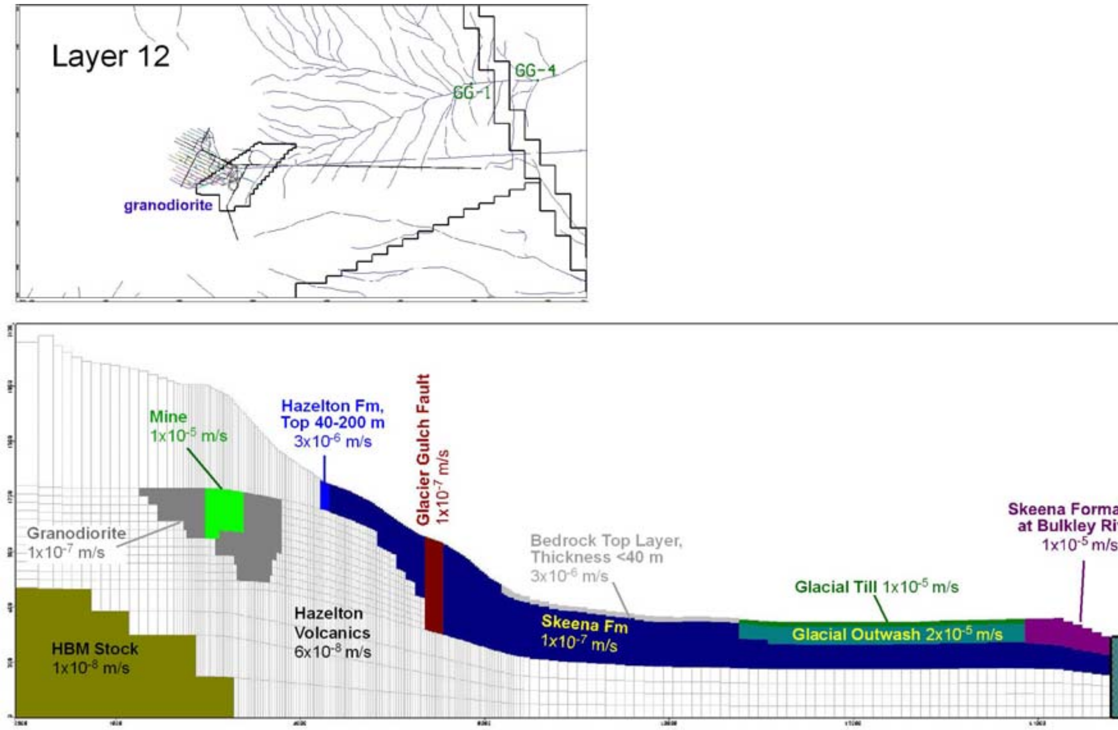


Figure 41. Enlarged Granodiorite Area for Transport Simulations, Layer 12 and Row 102 (2X Vertical Exaggeration)



Increasing the area of the granodiorite to fit the observed flux contributions to Glacier Gulch Creek did not significantly change the calibration statistics of fluxes computed previously. The normalized root mean squared error is 4.7% (residual mean of 22 m) for all head calibration targets, and 6.8% (residual mean of -3.5 m) for the site targets. The predicted flow to the 1066 Adit is 11 L/s. The predicted peak discharge during 700 Adit development is 42 L/s, and during mining the predicted peak flux is 51 L/s, when it is assumed the entire mine begins to drain on day 1 of operation. At the end of 700 Adit development, the model predicts a discharge rate of 30 L/s, and at the end of mining, it predicts 25 L/s of flow.

Therefore, the final calibration, Calib 3, resulted in fluxes similar to those of Calib 1A and Calib 2 (see Table 6). Transport simulations based on Calib 3 are discussed below.

Transport Simulation Results – Relative to Current Conditions

In the groundwater transport simulations with MT3D Version 5.2, a constant concentration condition of 100% was applied at all granodiorite and mine cells, shown in Figures 40 and 41. The model did not simulate adsorption/absorption to rock surfaces or degradation. The longitudinal dispersivity for the transport simulations was 10 m, the default value for this parameter. Lateral horizontal and vertical dispersivities were assigned to be 1 m and 0.1 m, respectively. The Upstream Weighting solution method was used, with the default options.

A first set of transport simulations were completed to evaluate the expected changes in groundwater chemistry relative to current conditions. These post-mining transport results were computed using the steady state post-mining head distribution for Calib 3. These post-mining transport results indicate that, because of the mine's location in a groundwater recharge zone (i.e., near the top of the mountain), pathlines from the mine sink to deeper strata just downgradient of the mine and rise to surface near the creeks. This was the same phenomenon observed in the pathlines.

Predicted concentrations by layer 30 years after the end of mining are shown in Figures 42 and 43. In shallow layers, the zone of influence of groundwater from the granodiorite is narrow, constrained by the fact that groundwater discharges to Glacier Gulch Creek (Figure 42). At greater depth, the influence of Glacier Gulch Creek is minor, and transport is directed toward Lake Kathlyn and the Bulkley River (Figure 43).

The predicted concentration contours 100 years after closure are shown in Figures 44 through 46. Time series plots of predicted concentrations at existing private wells and existing and proposed monitoring wells are shown in Figures 47 and 48.

The results show that the transport rate is low. It further indicates that, even after 100 years, the percent contribution of groundwater from the granodiorite to all the existing supply wells included in the simulation will be less than half of one percent (Figure 47). At strategically located monitoring wells uphill of the existing supply wells, the contribution of granodiorite-affected groundwater will reach 40% after 100 years.

Figure 42. Predicted Concentrations (0.1%, 1%, 10% and 50% of mine concentration) at Time=30 years after closure, Layers 2 and 5

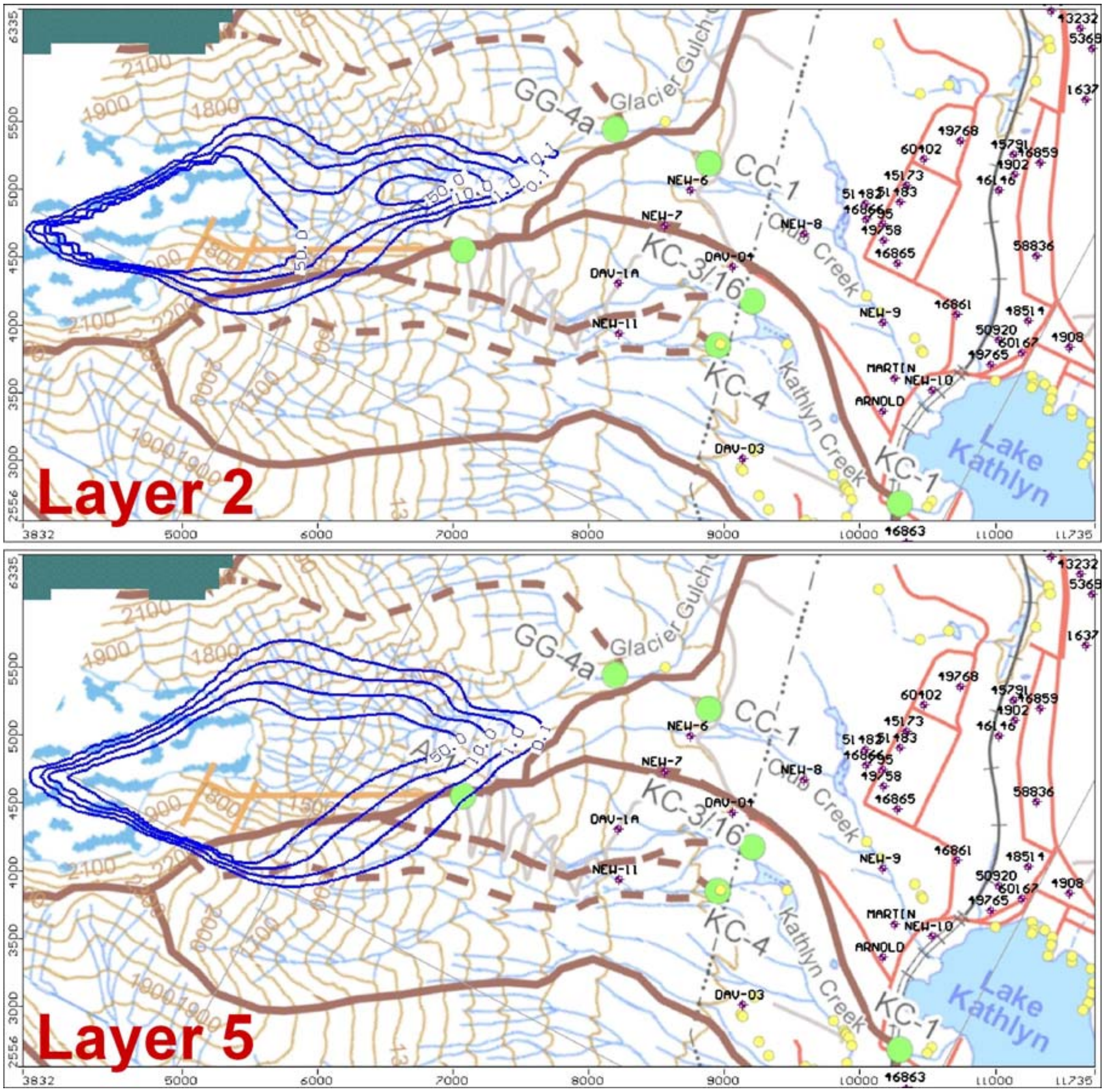


Figure 43. Predicted Concentrations (0.1%, 1%, 10% and 50% of mine concentration) at Time=30 years after closure, Layers 8 and 11

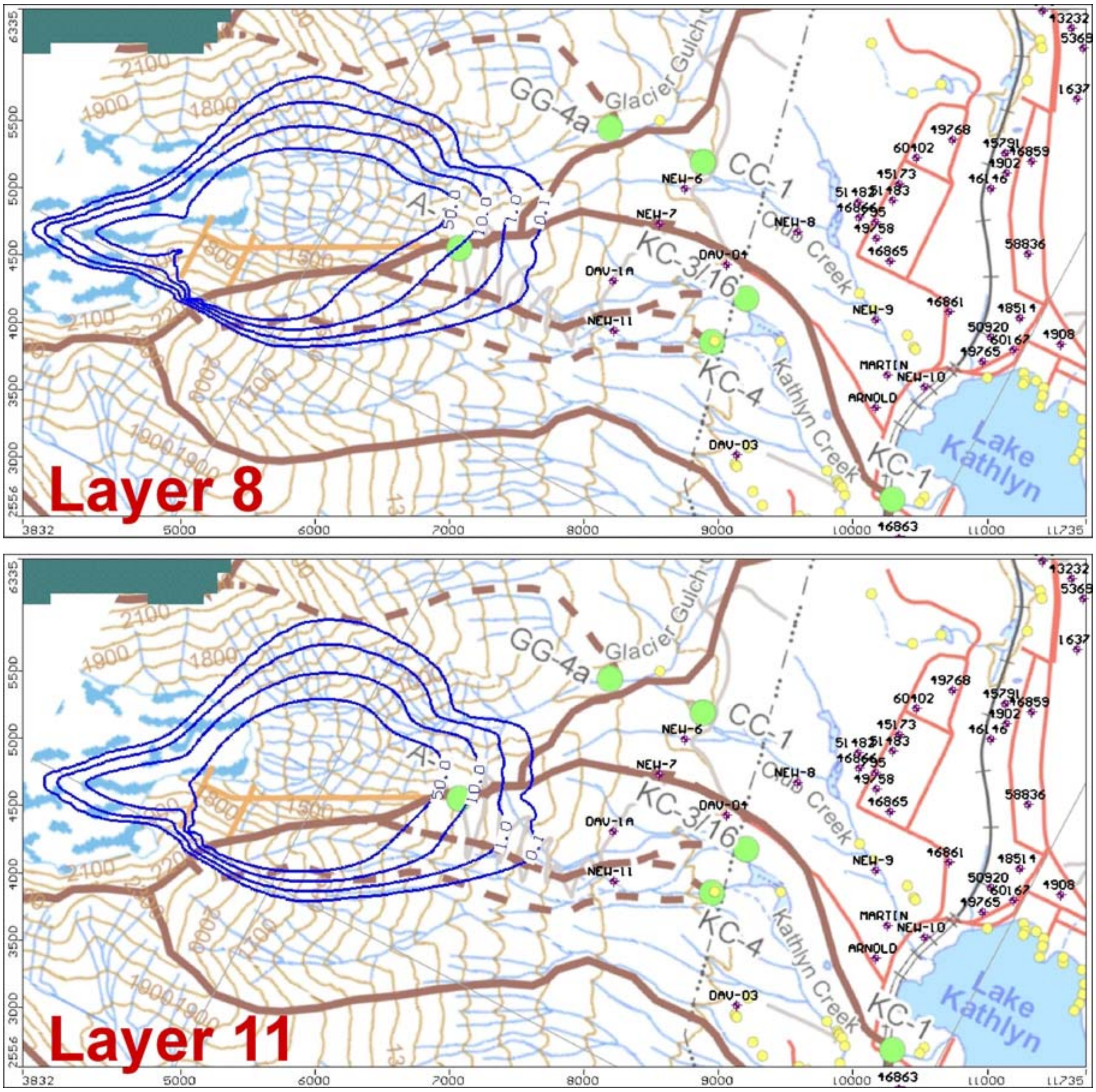


Figure 44. Predicted Concentrations (0.1%, 1%, 10% and 50% of mine concentration) at Time=100 years after closure, Layers 2 and 5

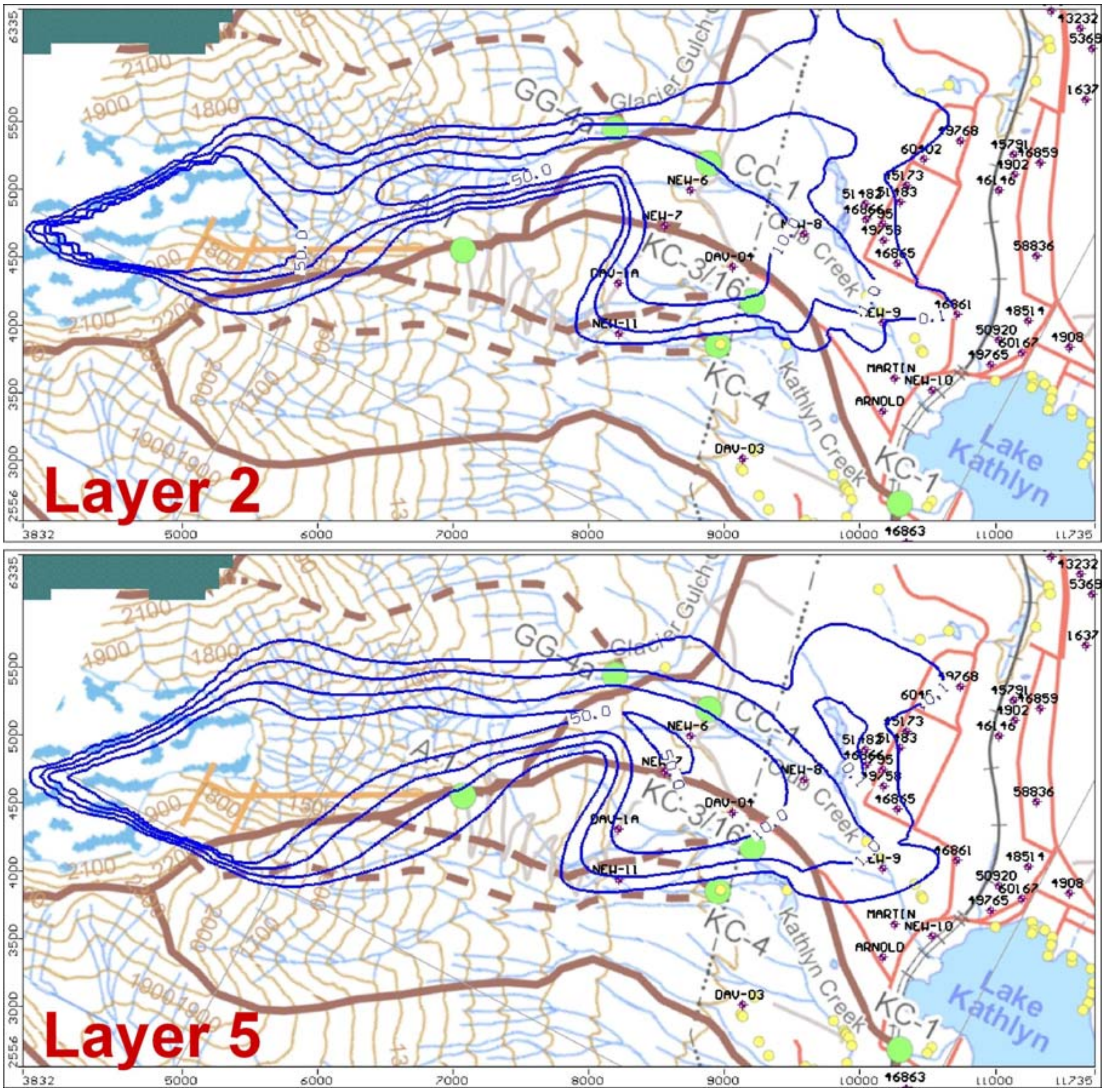


Figure 45. Predicted Concentrations (0.1%, 1%, 10% and 50% of mine concentration) at Time=100 years after closure, Layers 8 and 11

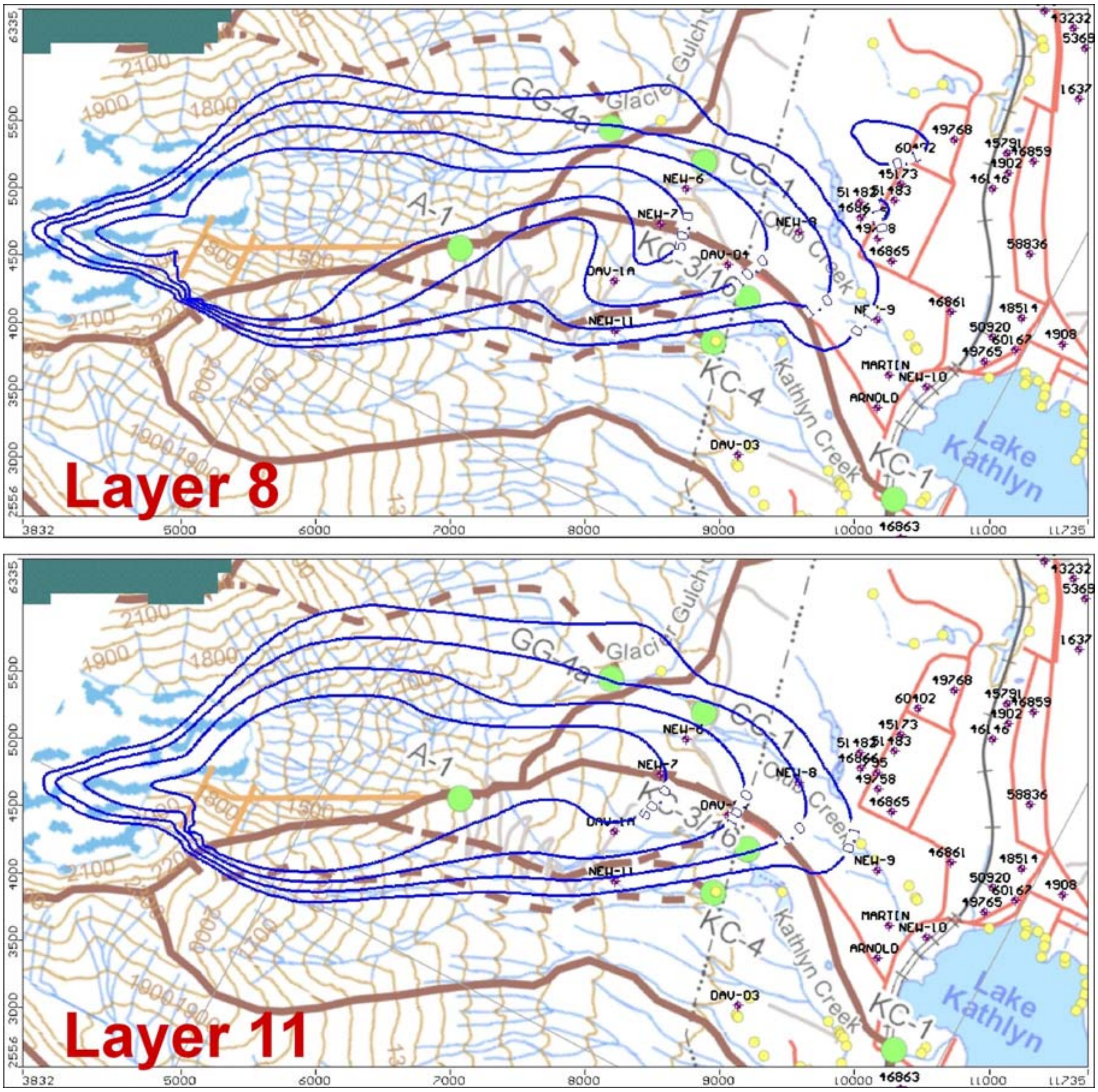


Figure 46. Predicted Concentrations (0.1%, 1%, 10% and 50% of mine concentration, Row 102

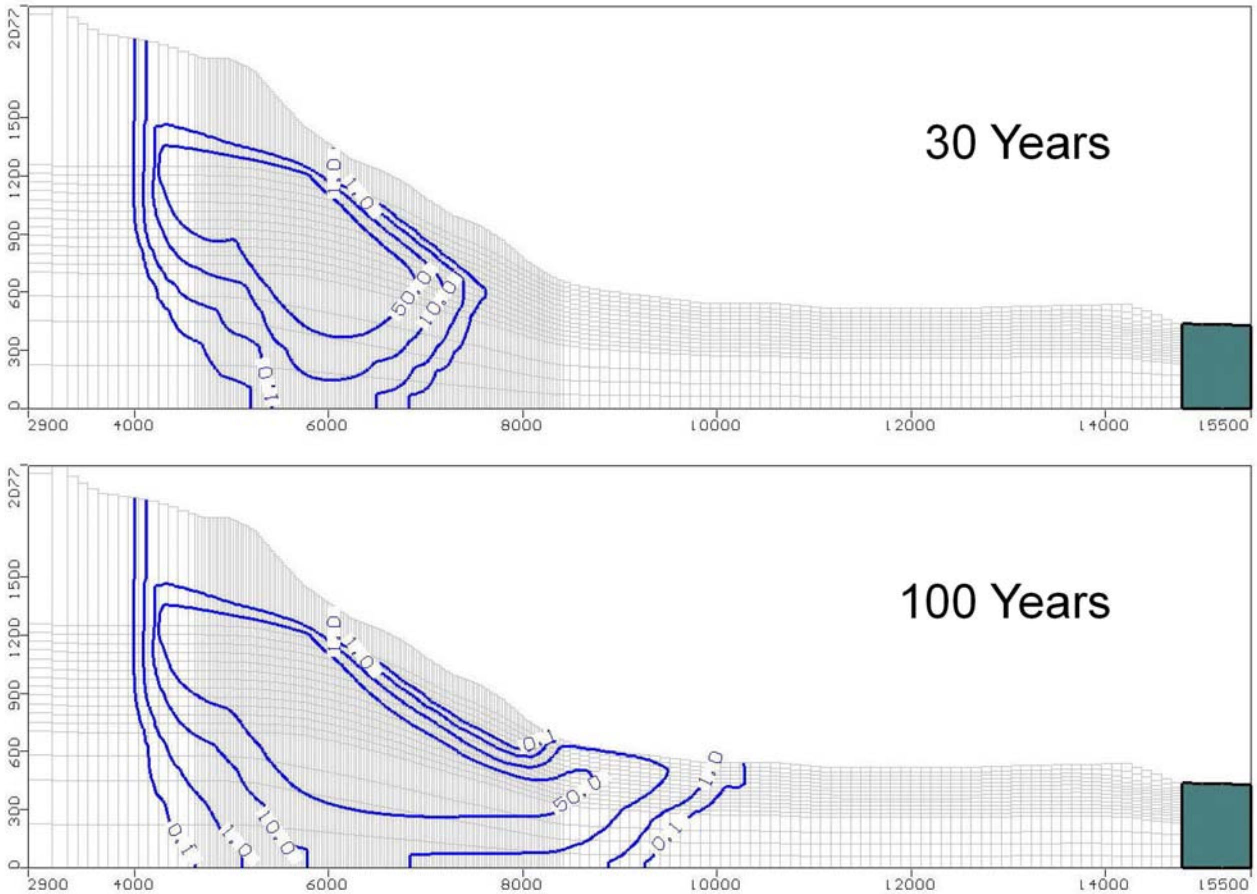


Figure 47. Predicted Concentration in Supply Wells, to 100 Years Post-Mining

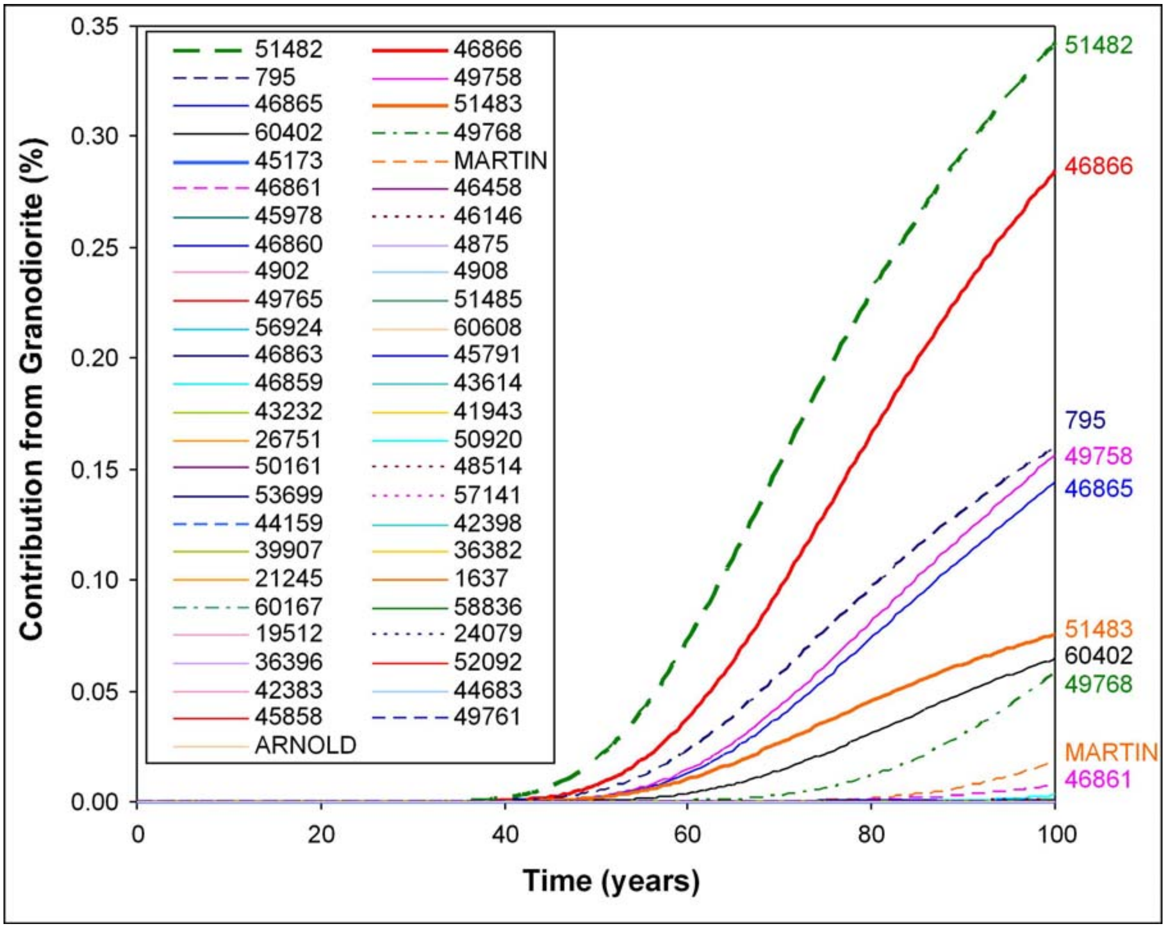
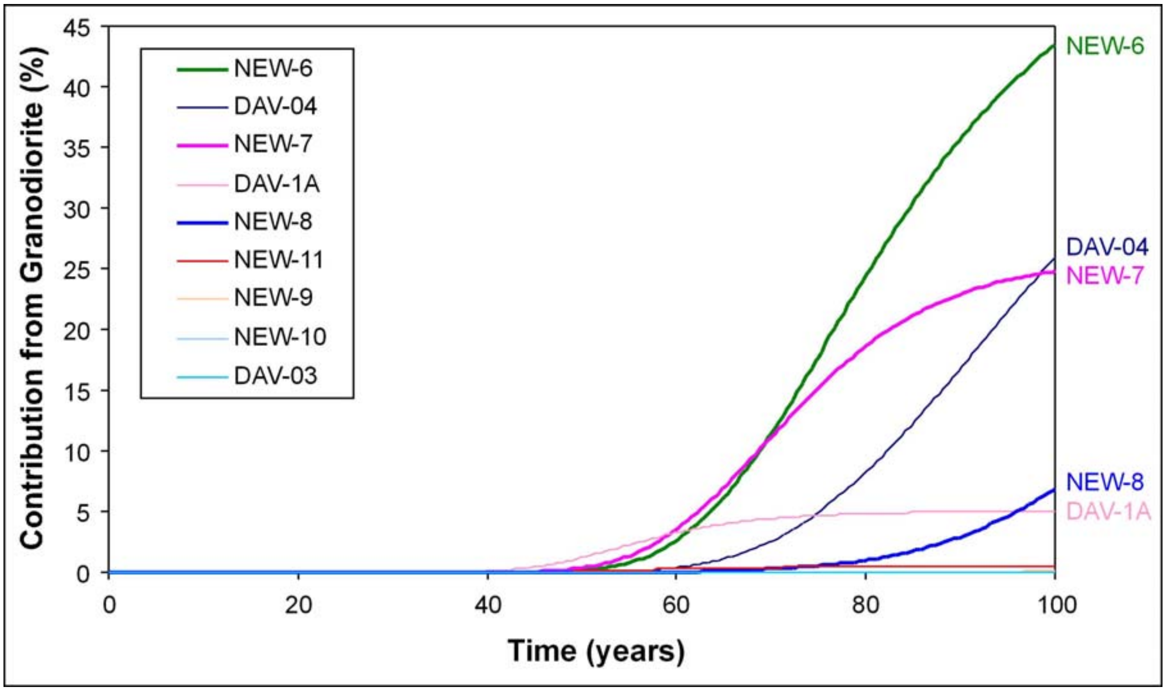


Figure 48. Predicted Concentration in Existing and Proposed Monitoring Wells, to 100 Years Post-Mining



Transport Simulation Results – Relative to 1960 Conditions

A second set of simulations included a prior simulation of the contribution of groundwater from the granodiorite prior to the installation of the 1066 Adit. These were multi-part simulations. First, pre-adit simulations were conducted to a period of 450 years, tracking groundwater from the granodiorite zone to downgradient locations. This first simulation was followed by a 50-year transient flow and transport simulation with only the 1066 Adit is operational. This was followed by 15 months of 700-Adit development and 10 years of mining. Finally, 500 years of transient post-closure simulation were completed. Time series plots of wells with non-negligible impacts are shown in Figure 49 and 50.

The runs showed that none of the groundwater in the area of the private wells received a contribution from granodiorite of greater than approximately 2% prior to installation of the 1066 Adit. In the monitoring network, the percent contribution from the granodiorite is predicted to have been approximately 50% at NEW-6 prior to development of the 1066 Adit. The model predicts that the percent contribution from the granodiorite dropped after installation of the 1066 Adit and will further drop during and for several decades after mining. Eventually, the percent contribution of groundwater from the granodiorite is expected to rise to and slightly above pre-1066-Adit levels. The increase over pre-1066 levels is due to the increased local hydraulic conductivity in the mined out areas. The eventual percent contribution from granodiorite-affected groundwater is expected to return to levels above 20%

in some of the monitoring wells (Figure 50). However, in none of the existing water supply wells at the base of the mountain is the percent contribution from groundwater contacting granodiorite predicted to increase above 3% (Figure 49).

Figure 49. Predicted Concentration in Supply Wells, Long-term Transport Simulations

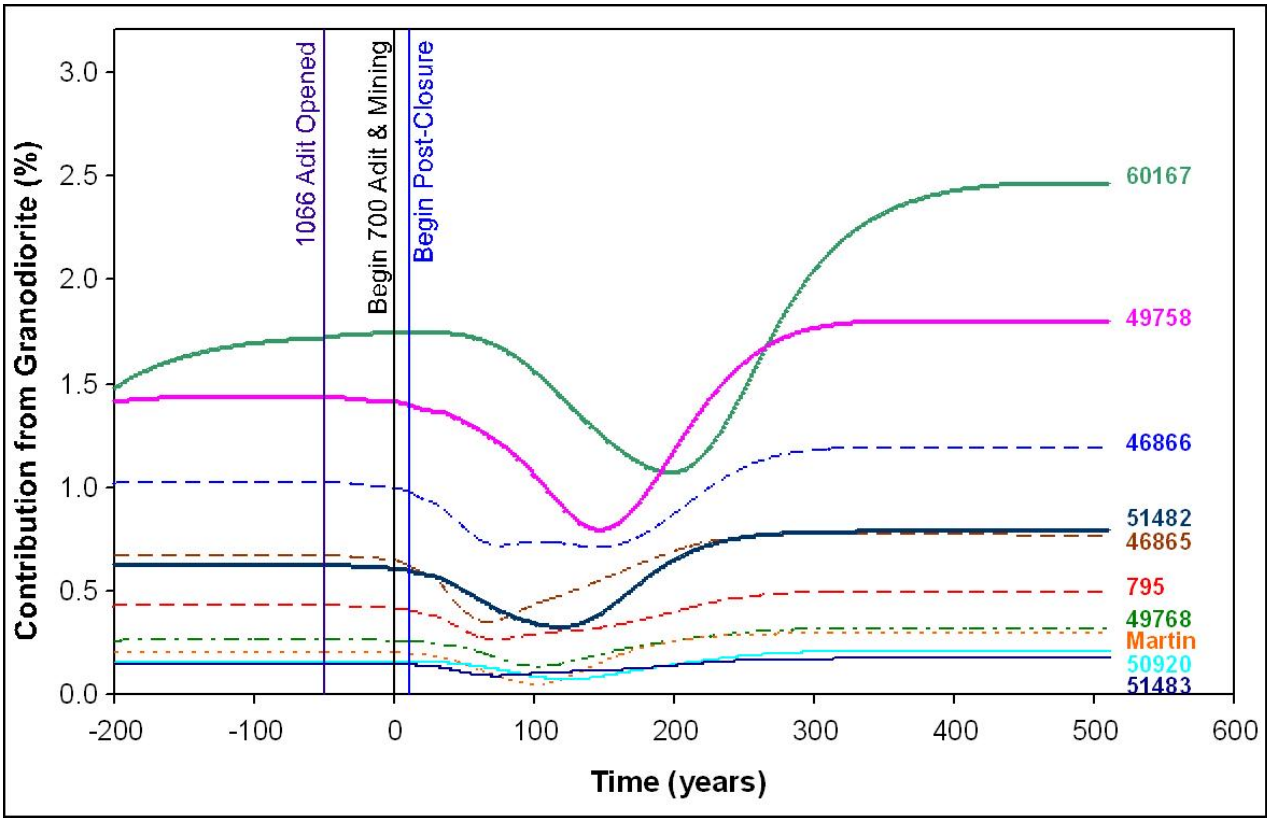
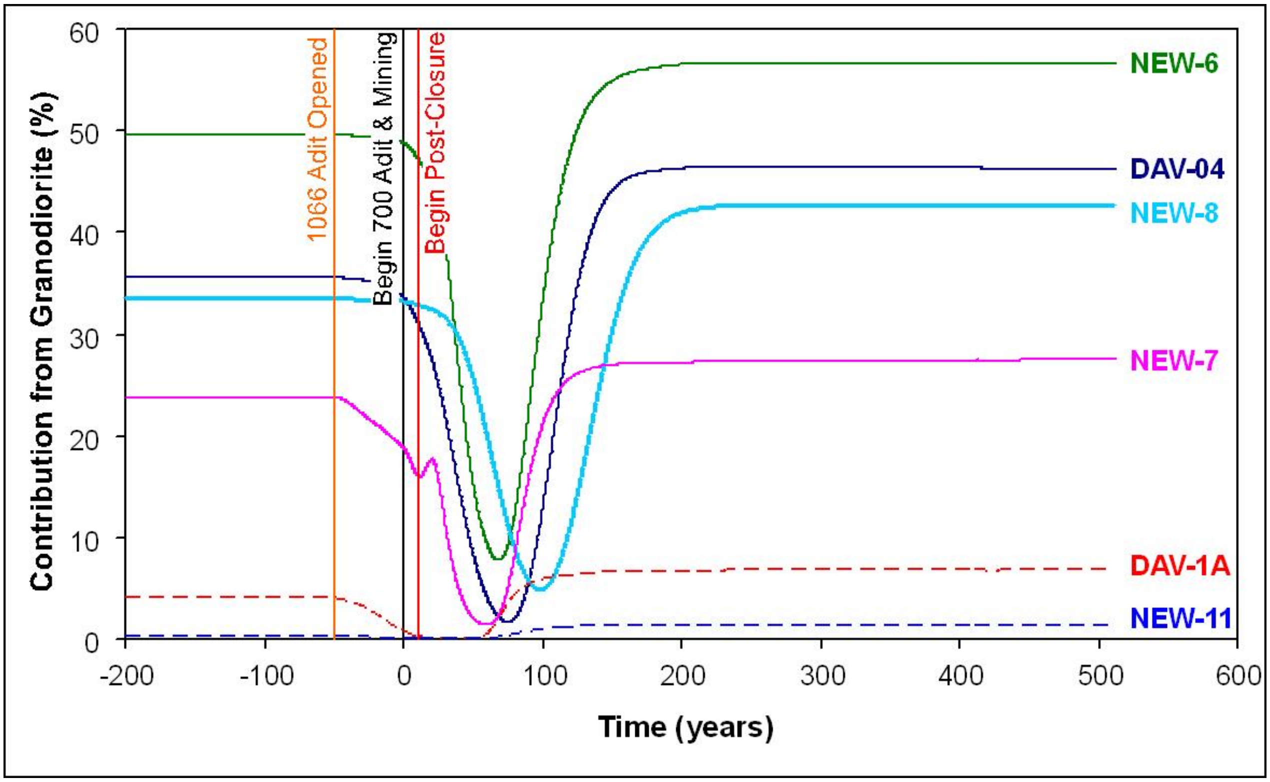


Figure 50. Predicted Concentration in Existing and Proposed Monitoring Wells, Long-term Transport Simulations



Monitoring Recommendations

Because the likely discharge points for groundwater from the granodiorite are relatively near the mine, the monitoring network will be more straightforward than if the main discharge point was the Bulkley River. Figure 51 shows locations of current and additional monitoring wells recommended for this project. The wells are shown as purple squares in Figure 51. Hydrology sampling sites are shown as green circles in the background. In addition to the monitoring wells, a comprehensive survey of seeps and springs in the mine area should be completed, particularly in the upper reaches of Glacier Gulch Creek. Identified seeps should be sampled for both water discharge and water quality.

Figure 51. Recommended Monitoring Network

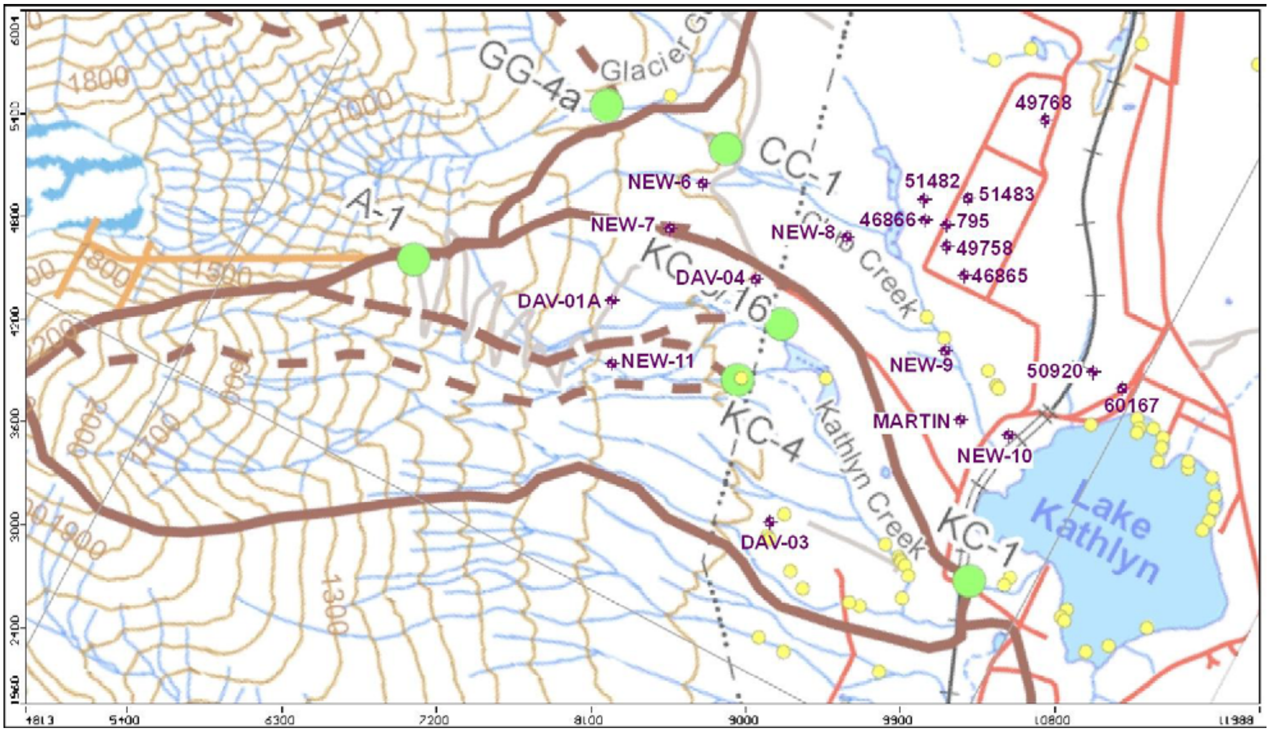


Table 17 shows the recommended frequency of water quality sampling. At the end of the mining period and again at the end of the first 10 years of closure, I recommend that the monitoring frequencies be reviewed and revised.

Table 17. Recommended Sampling Frequency for Water Quality Monitoring Points

	Sampling Interval (months) During:			
Sampling Point(s)	**Pre-Mining Period**	**700 Adit Development**	**Mining Period (10 years)**	**Post-Closure (first 10 years)**
NEW-6 to NEW-11, DAV-01 to DAV-04	3	6	6	6
Supply Wells (10 wells as shown in Figure 51)	24	None recommended	24	24
Seeps	3	3	3	3

Limitations

The assessment presented herein is based on a groundwater model. There are a number of uncertainties inherent to this type of analysis. The accuracy of the model will depend on the quality and quantity of data and the timeframe over which the data were collected. Furthermore, model calibration is non-unique, meaning that more than one set of parameters can lead to a model solution that meets the calibration targets. Examples of the non-uniqueness of the model are presented above. It is possible that this analysis has not been exhaustive and that there exist other viable parameter combinations that were not considered.

Closure

I trust that the model and this report provide the information that you require at this time. Should you have any questions, please contact me.

Yours truly,

H. Jean Cho, PhD, PEng

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Tiedeman, Claire R. and Paul A. Hsieh, "Assessing an open-well aquifer test in fractured crystalline rock," *Ground Water*, vol. 39, no. 1, pp. 68-78, 2001.